Modeling Prediction and Control of Saltwater Intrusion in a Coastal Aquifer of Andhra Pradesh India

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CERTIFICATE

It is certified that the work contained in the thesis entitled "**Modeling Prediction and Control of Saltwater Intrusion in a Coastal Aquifer of Andhra Pradesh India**", by " **Harikrishna Vennalakanti**" has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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ABSTRACT

The saltwater intrusion in a coastal aquifer is a highly complex and non linear process. The management of coastal aquifers requires careful planning of withdrawal strategies for control and remediation of saltwater intrusion. The predication of future saltwater distribution in the aquifer and possible strategies for controlling saltwater intrusion may be possible by simulating the processes in the coastal aquifers, through mathematical models. A 3-D, transient, density dependent, finite element based flow and transport simulation model is implemented for selected area in the coastal region of Nellore district of Andhra Pradesh, India. The available data are used as input for implementing the numerical simulation model for the study area. The numerical model is calibrated for two years time period between July 2000 and July 2002, both in terms of hydraulic heads and salt concentration. The calibrated model is further validated for next years in terms of head and salt concentration with the available data for July 2002 and July 2004. This calibrated and partially validated simulation model is used to evaluate the effectiveness of few pumping scenarios on the saltwater intrusion process in the study area. These limited evaluations show the potential for using a calibrated flow and transport simulation model for prediction of saltwater distribution in the aquifer, and to evolve planned pumping strategies for control of saltwater intrusion.

Dedicated To GOD

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Harikrishna Vennalakanti

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

Chapter 1

INTRODUCTION

1.1 Introduction

Coastal aquifers are important sources of water in coastal regions. As population density in many coastal areas increased, need for fresh water also increased. Along with the population, industrial and agricultural growths in these areas accelerate the exploitation of groundwater. Over exploitation of groundwater from coastal aquifers may result in intrusion of saltwater in the aquifer. This is mainly due to excess withdrawal of groundwater compared to the recharge rate, and unplanned pumping locations and pumping patterns. Saltwater intrusion often results in:

- Loss of drinking water resource as existing drinking water well locations are affected by saltwater intrusion.
- Increase in soil salinity and therefore growing of crops in that region become difficult due to saline soil and saline water.
- Possible relocation of habitants from villages due to non availability of productive soils and drinking water.

On the whole, contamination of coastal aquifers may lead to serious consequences on environment, ecology and economy of that region. The study presented in this thesis is aimed at modeling and prediction of saltwater intrusion in a real life study area in the coastal belt of Andhra Pradesh in India.

Groundwater is a major source of water. There maintaining of its quantity and quality is essential. Often, the management of coastal aquifers requires, careful planning of withdrawal strategies for control and remediation of saltwater intrusion in coastal aquifers.

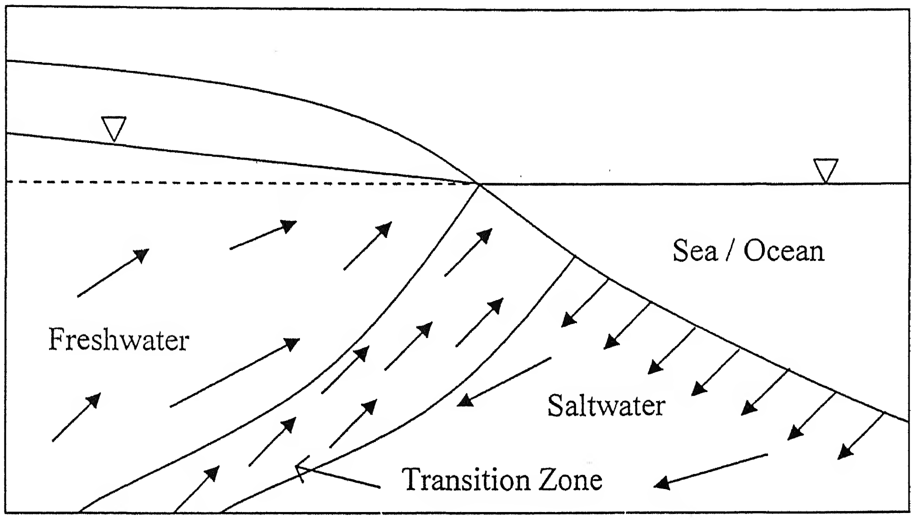
Such strategies can be evolved only if, the physical process involved in the coastal aquifers are simulated through models. Generally these models are mathematical models, which require solution using numerical techniques.

A mathematical model once implemented for a specific study area after calibration and validation can be used to simulate the response of the aquifer system to various pumping and recharge strategies. These simulation results are essential to predict the response of the aquifer system and to design possible remedial measures to control the saltwater intrusion process.

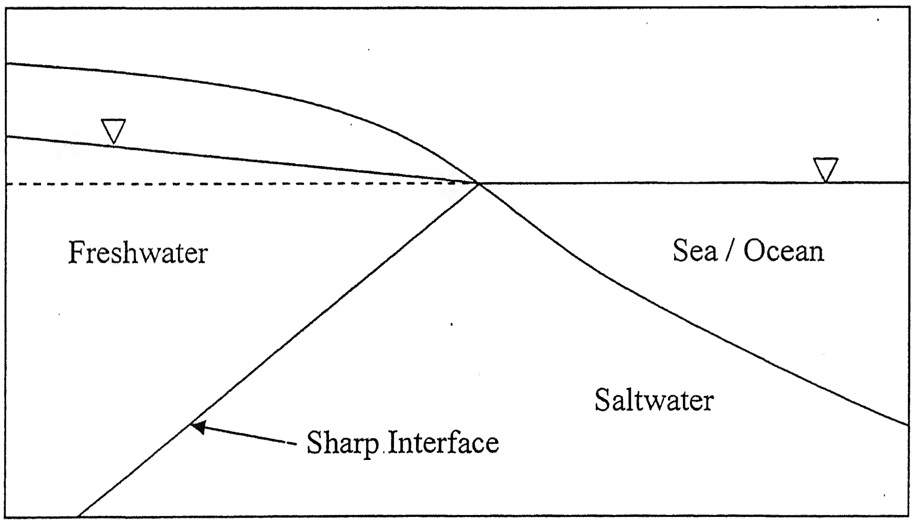
A 3-D, transient, density dependent, finite element based flow and transport simulation model is implemented for the selected area in Nellore District, in Andhra Pradesh, India. This area is extensively utilizing pumped water from the underlying aquifers for agricultural, domestic and aqua cultural uses. The simulation model is calibrated using observed head and concentration data. The calibrated model is then utilized for evaluating the impact of adapting few pumping strategies for controlling the saltwater intrusion process.

If any two liquids are in contact, they are subjected to opposing hydrodynamic mechanisms. Similar dynamic balance is present between freshwater and saltwater, but to over exploitation of groundwater disturbs the existing balance between them and saltwater starts intruding in landward direction. Due to higher density of saltwater, it underlies the freshwater because of hydrodynamic mechanism. At the same time due to hydrodynamic dispersion a mixing zone of varying density also exists between saltwater and freshwater. This zone is called transition zone or zone of dispersion. Figure 1.1(a) shows vertical section of an unconfined aquifer with the transition zone. The density of mixed fluid in this zone gradually increases as the water becomes more salty. The transition zone thickness

will vary; if the thickness is relatively small when compared to the aquifer dimensions. In these cases, both saltwater and freshwater are considered as immiscible fluids and the interface between them is considered as sharp interface. Figure 1.1(b) shows sharp interface between freshwater and saltwater in an unconfined aquifer.



(a) With Transition Zone



(b) Sharp Interface Approximation

Figure 1.1: Vertical cross section of an unconfined coastal aquifer

Sharp interface approach simplifies the saltwater intrusion problem but it is not applicable when the dispersion zone is quite considerable. So to solve the real world saltwater intrusion problems one has to consider transition zone between freshwater and saltwater. With the consideration of transition zone saltwater intrusion process becomes highly complex and nonlinear. In this case both flow and transport parts become density dependent.

The behavior of saltwater intrusion problem can be described in to two differential mathematical equations namely flow and transport equations. These governing equations are solved simultaneously to simulate the saltwater intrusion process. The flow and transport equations are density dependent. Here flow and transport equations are coupled by density coupling coefficients and Darcy's velocities (Huyakorn *et al.*, 1987). Due to coupling terms, saltwater intrusion process becomes nonlinear and is solved by iteration process between these two governing equations. Therefore, simulation of saltwater intrusion along with density dependence condition makes it complex and time consuming procedure. In the present study, density dependence of flow and transport processes is considered.

In the past the problem of contaminating the coastal aquifers around the world had been reported by many researchers. Rouve and Stoessinger (1980) reported the contamination of coastal aquifer in Madras, India due to saltwater intrusion. Sherif *et al.* (1986) described about saltwater intrusion of Nile delta aquifer in Egypt. Willis and Finney (1988) explained the same in coastal aquifer at Yun Lin basin in southwestern Taiwan. About this problem in Jahe river basin, Shandog province in China was reported by Cheng and Chen (2001) and suggested some remedial measures. In all the

above cases the main reason for saltwater intrusion in coastal aquifers is due to over exploitation of groundwater due to lack of proper management measures.

Some of the important works related to saltwater intrusion in aquifers are briefly described below.

1.2 Literature Review

There are two general approaches to analyze saltwater intrusion in coastal aquifers. One is disperse interface and another is sharp interface. The disperse interface is nothing but transition zone where the mixing of saltwater and fresh water occurs due to hydrodynamic dispersion this zone is called transition zone or zone of diffusion or zone of dispersion. The sharp interface approach simplifies the analysis by assuming that the transition zone is thin relative to the aquifer dimensions.

Saltwater intrusion simulations are generally performed assuming sharp salt and fresh water interface. Analytical solutions of sharp interface model for single homogenous aquifers have been developed by Henry (1959), Bear and Dagan (1964), Dagan and Bear (1968), Schmorak and Mercado (1969).

Lee and Cheng (1974) developed the two dimensional steady state seawater intrusion problems in coastal aquifers first by finite element technique by triangular elements. They considered the homogeneous isotropic aquifer.

Segol and Pinder (1976) used Galerkin-finite element method to solve the two dimensional movement of saltwater front dominated by advective transport.

Mercer *et al* (1980) presented a numerical simulation of saltwater interface motion. They assumed the partial differential equations describing the motion of saltwater and freshwater is separated by a sharp interface and the aerial equations were based on Dupuit

approximation and are obtained from partial integration over vertical direction. They used finite difference method. Another numerical model based on the sharp interface assuming the validity of Dupuit assumptions by Polo and Ramis (1983). They also considered finite difference method.

A quasi three dimensional finite difference based numerical model was developed by Essaid (1990). It simulates freshwater and saltwater flow separated by sharp interface; it has been developed to study on layered coastal aquifer systems. The model is applied for regional simulation of coastal groundwater conditions. The sharp interface approach, along with the assumption of horizontal flow with in aquifers and vertical flux through aquitards, allowed the simulation of coastal aquifer systems on an aerial scale.

Huyakorn *et al.* (1996) developed a sharp interface numerical model to simulate saltwater intrusion in multilayered coastal aquifer systems. They used Galerkin finite element method to discretize the governing equations and Newton- Raphson method with automatic time stepping in the model. This model is verified using three test problems which includes unconfined, confined and multilayered aquifer systems for steady state and transient flow simulations. After comparing both numerical and analytical solutions, they concluded that the proposed numerical schemes were efficient and accurate in tracking the location, lateral movement, and upconing of the freshwater-saltwater interface.

Guvanasen *et al.* (2000) developed a sharp interface saltwater simulation model to simulate regional groundwater flow and saltwater intrusion in Hernando County, Florida. The work was divided into two stages: one freshwater model development, based on MODFLOW- SURF code (HydeoGeoLogic 1996; Panday and Hyakorn 1996) and second one was sharp interface model development which was implemented using the SIMLAS (Saltwater Intrusion finite element Model for Layered Aquifer Systems) code, which is a

quasi-three dimensional, finite element code. Their results showed that the freshwater/saltwater interface will migrate landward less than 1.6km by 2050 from its 1994 position.

The sharp interface approach is not valid for situations where a transition from saltwater to freshwater region is not abrupt and if the width of transition zone is large which is greatly affected by hydrodynamic dispersion. At these conditions the simulation approach should consider dispersion effects. Henry (1964) first developed analytical solution for steady state salt distribution of a confined aquifer. Henry's steady state condition was modified to transient condition by Pinder and Cooper (1970) and presented first numerical solution of salt transport using the method of characteristics.

Lee and Cheng (1974) first presented a steady state two dimensional seawater encroachment by finite element method using triangular elements in the Biscayne aquifer at Cutler area. They first solved the Henry's problem and verified with their numerical scheme and then predicted the saltwater movement in the aquifer at cutler area, Florida.

In the same area (Cutler area of Biscayne aquifer, Florida), Segol and Pinder (1976) presented a two dimensional transient simulation of saltwater intrusion using Galerkin finite element approximation. They utilized the field observed data of chloride distribution before and after rain fall. They initially calibrated the model in steady state condition with the observed chloride distribution before rainfall and used this as initial condition for transient problem. The transient problem results showed the sea ward movement of saltwater front in response to the heavy rainfall; this had been compared with chloride distribution after rain fall.

Gupta *et al.* (1984) developed a numerical simulation model (FE3DGW) based on finite element scheme to simulate a three-dimensional steady and transient behavior of

large, natural, multilayered groundwater systems. The model applications were used for simulation of groundwater reservoir beneath long Island, New York. The finite element model results were compared with electric analog model of the same region. Voss (1984) developed finite element based SUTRA code for simulation of density dependent saltwater intrusion process in two dimensional coastal aquifers.

Huyakorn *et al.* (1987) developed a three-dimensional finite element model was developed for the simulation of saltwater intrusion. The model was capable of handling single and multiple coastal aquifers systems with either a confined or phreatic top aquifer. The model can be used for either for three-dimensional or quasi three-dimensional simulations. This model was tested for both steady and transient cases of Henry's problem.

Sherif *et al.* (1988) developed a steady sate two-dimensional finite element simulated model to simulate saltwater intrusion phenomenon in a confined and leaky aquifers. They considered heterogeneity and anisotropy and used Galerkin technique. First they verified model with the problems from literature and then applied to the Nile delta aquifer in Egypt.

Galeati *et al.* (1992) presented a finite element density dependent transport model in unconfined coastal aquifers by means of Eulerian-Lagrangian solution procedure. They adapted various numerical schemes like coupled, partially coupled and completely decoupled modes to test the dependency of fluid density on salt concentration affects the numerical solutions. They found depth and rate of saltwater penetration inland was more sensitive to the magnitude and spatial distribution of hydraulic conductivities than the numerical methods.

Lin *et al.* (1997) developed a three dimensional finite element computer model (FEMWATER) for simulating density dependent flow and transport in variable saturated media: version 3.1.

Cheng *et al.* (1998) developed a two-dimensional finite element model for density dependent flow and transport through saturated and unsaturated porous media. This model is capable of handling different simulations like flow alone, transport alone and combined flow and transport. They employed both conventional finite element methods and hybrid Lagrangian-Eulerian finite element methods in transport module and Galerkin finite element method in flow module.

Cheng and Chen (2001) applied a three-dimensional variable density flow and transport model to solve a real time problem considering tidal effect. The parameters are estimated based on long term observational data of hydraulic head and chloride concentration. Several remedial measures are also suggested to prevent the saltwater intrusion problem in the aquifer.

The aim of this study is to utilize one of the models. A 3D, transient, density dependent, flow and transport finite element numerical model FEMWATER (Lin *et al.*, 1997) for simulating the aquifer system in the chosen study area.

1.3 Objective of the thesis work

The objective the thesis is to model the saltwater intrusion process in a coastal aquifer for a study area located in the Nellore district of Andhra Pradesh, India.

A three-dimensional saltwater intrusion model FEMWATER (Lin *et al.*, 1997) is calibrated for the given study area. The calibrated model is then utilized for predicting the future saltwater intrusion scenario for existing withdrawal patterns and for specified management strategies aimed at controlling the saltwater intrusion process.

Field data of the site is utilized for the implementation of the simulation model. The steps involved are

- Collection of all head, concentration, pumping data for the study area, along with boundary conditions and parameter estimates.
- Implementation of a three-dimensional, finite element based numerical saltwater intrusion model for the coastal aquifer study area.
- Calibration of the developed model for the study area.
- Using the calibrated model for predicting the future saltwater intrusion scenarios and evaluating the management strategies for possible control of saltwater intrusion.

Chapter 2

Numerical Simulation Model

Chapter 2

Numerical Simulation Model

2.1 Introduction

The phenomenon of saltwater intrusion in a coastal aquifer can be mathematically represented by two partial differential equations namely flow and transport equations. These two partial differential equations are coupled by density and Darcy velocity terms. The saltwater intrusion problem becomes highly non linear due to this coupling of two partial differential equations. These nonlinear equations are solved simultaneously to solve the saltwater intrusion problem. Therefore, simulation of saltwater intrusion along with density dependence condition makes it complex and time consuming procedure.

Many numerical models are there to solve the saltwater intrusion problem in coastal aquifers. In this study, a finite element based simulation model FEMWATER (Lin *et al.*, 1997) is used. FEMWATER is a three-dimensional finite element, transient, density driven flow and transport ground water model. The FEMWATER numerical model with input and output pre processes and post processes is utilized in the study. It can be used to simulate flow and transport in both the saturated and the unsaturated zone. Furthermore, the flow and transport can be coupled to simulate density dependent problems such as salinity intrusion.

One of the advantages of the finite element method used by FEMWATER is that model boundaries and stratigraphic units can be modeled precisely. Furthermore,

since FEMWATER simulates flow in the unsaturated zone, the entire aquifer is modeled and sources and sinks can be directly represented in the mesh and boundary conditions can be represented accurately. The disadvantage of FEMWATER is that it is memory intensive, solutions can be time-consuming.

The FEMWATER is a three-dimensional finite element, saturated/unsaturated, density driven flow and transport model is used to simulate the saltwater intrusion problem in the selected study area. The description of the governing equations of FEMWATER briefly explained below.

2.2 Governing Equations.

FEMWATER is designed to solve the following system of governing equations which describe flow and transport through saturated – unsaturated porous media. The governing equations for flow are basically the modified Richards equation as follows

2.2.1 Governing equations for flow

The 3D flow equation may be written as (Lin *et al.*, 1997)

$$\frac{\rho}{\rho_o} F \frac{\partial h}{\partial t} = \nabla . \left[K . \left(\nabla h + \frac{\rho}{\rho_o} \nabla z \right) \right] + \frac{\rho^*}{\rho_o} q \tag{2.1}$$

Where

$F =$ Storage coefficient

$h =$ Reference hydraulic head, [L].

$t =$ Time, [T]

$K =$ Hydraulic conductivity tensor, [LT $^{-1}$]

$z =$ Potential head, [L]

$q =$ Volumetric flow rate of Source and/or sink, $[L^3 T^{-1} L^{-3}]$

$\rho =$ Water density at chemical concentration C, $[M L^{-3}]$

$\rho_o =$ Referenced water density at zero chemical concentration, $[M L^{-3}]$

$\rho^* =$ Density of either the injection fluid or the withdrawn water, $[M L^{-3}]$

The storage coefficient F is defined as

$$F = \alpha'\frac{\theta}{n} + \beta'\theta + n\frac{dS}{dh} \tag{2.2}$$

Where

$\theta =$ Moisture content

$n =$ Porosity of the medium

$S =$ Saturation

$\alpha' =$ Modified compressibility of the medium, $[L^{-1}]$

$\beta' =$ Modified compressibility of the water, $[L^{-1}]$

α' and β' further defined as

$\alpha' = \alpha\, \rho_o\, g$; $\beta' = \beta\, \rho_o\, g$

Where

$\alpha =$ Compressibility of the medium, $[M^{-1} L T^2]$

$\beta =$ Compressibility of the water, $[M^{-1} L T^2]$

$g =$ Gravity, $[L T^{-2}]$

The hydraulic conductivity K is dependent on fluid density (ρ), viscosity (μ) and acceleration due to gravity (g). The hydraulic conductivity is defined as

$$K = \frac{\rho g}{\mu}k = \frac{(\rho / \rho_o)}{\mu / \mu_o}\frac{\rho_o G}{\mu_o}k_s k_r = \frac{(\rho / \rho_o)}{\mu / \mu_o}k_{so}k_r \tag{2.3}$$

Where

μ = Dynamic viscosity of water at chemical concentration, [M L^{-1} T^{-1}]

μ_o = Referenced dynamic viscosity at zero chemical concentration, [M L^{-1} T^{-1}]

k = Permeability tensor, [L^2]

k_s = Saturated permeability tensor, [L^2]

k_r = Relative permeability or relative hydraulic conductivity, [L T^{-1}]

k_{so} = Referenced saturated hydraulic conductivity tensor, [L T^{-1}]

The referenced value is usually taken at zero chemical concentration. The density and dynamic viscosity of water are functions of chemical concentration and are assumed to take the following form

$$\frac{\rho}{\rho_o} = a_1 + a_2 C + a_3 C^2 + a_4 C^3 \tag{2.4a}$$

$$\frac{\mu}{\mu_o} = a_5 + a_6 C + a_7 C^2 + a_8 C^3 \tag{2.4b}$$

Where a_1, a_2,...a_8 are the parameters (L^3/M)used to define concentration dependence of water density and viscosity and C is the chemical concentration (M/L^3)

In the case of saltwater intrusion, the constitutive relationship between fluid density and concentration takes the form:

$$\frac{\rho}{\rho_o} = (1 + \varepsilon c) \tag{2.5}$$

Where

c = Dimension less chemical concentration (actual one divided by maximum one)

ε = Dimensionless density reference ratio defined as

$$\varepsilon = \frac{\rho_{max}}{\rho_0} - 1 \tag{2.6}$$

Where ρ_{max} is the maximum density of the fluid

The Darcy velocity [L T^{-1}] is calculated as follows

$$V = -K.\left(\frac{\rho_o}{\rho}\nabla h + \nabla z\right) \tag{2.7}$$

2.2.2 Governing equations for transport

The governing equations for transport describe the material transport through groundwater systems. These equations are derived based on the laws of continuity of mass and flux. The major processes that are considered are advection, dispersion/diffusion, adsorption, decay, biodegradation and injection/ withdrawal. The transport equation is written as (Lin *et al.*, 1997)

$$\theta\frac{\partial C}{\partial t} + \rho_b\frac{\partial S}{\partial t} + V.\nabla C - \nabla.(\theta D.\nabla C) = -\left(\alpha'\frac{\partial h}{\partial t} + \lambda\right)\left(\theta C + \rho_b S\right)$$
$$-\left(\theta K_W C + \rho_b K_S S\right) + m - \frac{\rho^*}{\rho}qC + \left(F\frac{\partial h}{\partial t} + \frac{\rho_o}{\rho}V.\nabla\frac{\rho}{\rho_o} - \frac{\partial\theta}{\partial t}\right)C \tag{2.8}$$

Where

6 = Moisture concentration

ρ_b = Bulk density of the medium, [M L^{-3}]

C = Material concentration in aqueous phase, [M L^{-3}]

S = Material concentration in adsorbed phase.

t = Time, [T]

∇ = Del operator

D = Dispersion tensor, [$L^2 T^{-1}$]

α' = Compressibility of the medium, [$M^{-1} L T^2$]

h = Pressure head, [L]

λ = Decay constant, [T^{-1}]

$m = q\,C_{in}$ = artificial mass rate, [$M L^{-3} T^{-1}$]

q = Volumetric flow rate of Source and/or sink, [$L^3 T^{-1} L^{-3}$]

C_{in} = Material concentration in the source, [$M L^{-3}$]

K_W = First order biodegradation rate constant through dissolved phase, [T^{-1}]

K_S = First order biodegradation rate through adsorbed phase, [T^{-1}]

F = Storage coefficient

The dispersion coefficient tensor D in equation is given by

$$\theta D = \alpha_T |V| \delta + (\alpha_L - \alpha_T)\frac{VV}{|V|} + \alpha_m \theta \tau \delta \tag{2.9}$$

Where

$|V|$ = Magnitude of V, [$L T^{-1}$]

δ = Kronecker delta tensor

α_T = Lateral dispersivity, [L]

α_L = Longitudinal dispersivity, [L]

α_m = Molecular diffusion coefficient, [$L^2 T$]

τ = Tortuosity

The flow and transport processes are represented by equations 2.1 and 2.8 respectively. These two equations are coupled together by the density coupling coefficient, and by the Darcy velocities which makes the saltwater intrusion problem highly nonlinear. Decay, adsorption, biodegradation and artificial mass flow are neglected. A finite element based simulation model, FEMWATER is used in this study to solve these two governing equations simultaneously to give solutions of head and concentration over period of simulated time.

The simulation model FEMWATER uses Galerkin finite element technique to approximate the flow equation and uses weighted residual finite element method to approximate the transport equation.

Advantages of FEMWATER

- Anisotropy and heterogeneity of aquifer are easily taken care of.
- Formulation of special formulae to incorporate irregular boundaries is unnecessary.
- Computer storage and computational time can some times be saved because often fewer nodal points are needed to portray the region of interest to the same level of accuracy.

Chapter 3

Study area and Data Collection

Chapter 3

Study area and Data collection

3.1 Study area description

The study area chosen for the thesis is a coastal aquifer located down stream the of Penna river delta of Nellore district in Andhra Pradesh in India. This coastal aquifer is chosen because it is already affected with saltwater intrusion problem. The study area covers two mandals about 355 km^2. This area is extensively utilizing pumped water from the underlying aquifers for agricultural, domestic and aquacultural uses. In this study area, water levels in the villages close to coastal line are already below the mean sea level. This is mainly due to huge requirement of water for aquaculture which is spreading in alarming rate in this area, and for paddy the major crop of the area which requires huge amount of water. Adding to this huge requirement of water, there is no considerable amount of rains which is the only source of recharging the coastal aquifer. The general features of the selected study area are described below.

General features of study area

Toposheet Number	: 66 B / 1 and 66 B / 2. (Survey of India)
Lat & Long	: $14^0 35' 24'' - 14^0 48' 36''$ & $79^0 57' 00'' - 80^0 10' 12''$
Drainage Basin	: Penna River
Area	: Consists of 2 mandals viz. Allur and Vidavalur; details of these mandals are given in table3.1.

Table 3.1: Details about two mandals.

Item	Allur mandal	Vidavalur mandal
No. of villages	15	10
Area	197 km^2	158 km^2
Population	52990	46793
Normal Rainfall	1133 mm	1141 mm
Major crop	Paddy	Paddy

(Source: Hand book of statistics, 2003-04, Nellore District by Chief Planning Office, Nellore)

3.2 Geology of the study area

The geographical location of study area is show in Figure 3.1. The study area falls under alluvium soil type. These soils comprises of admixtures of sand, silt and clay in various proportions. The quartz pebbles are invariably encountered at different depths in almost all places in alluvial areas. It is generally light brown to pale gray and sandy in nature. The thickness of coastal alluvium is very large as evident from the exploratory wells drilled by Central Ground Water Board (CGWB) in this area. Bed rock was not encountered even at drilling depths ranging from 250 to 500 m.

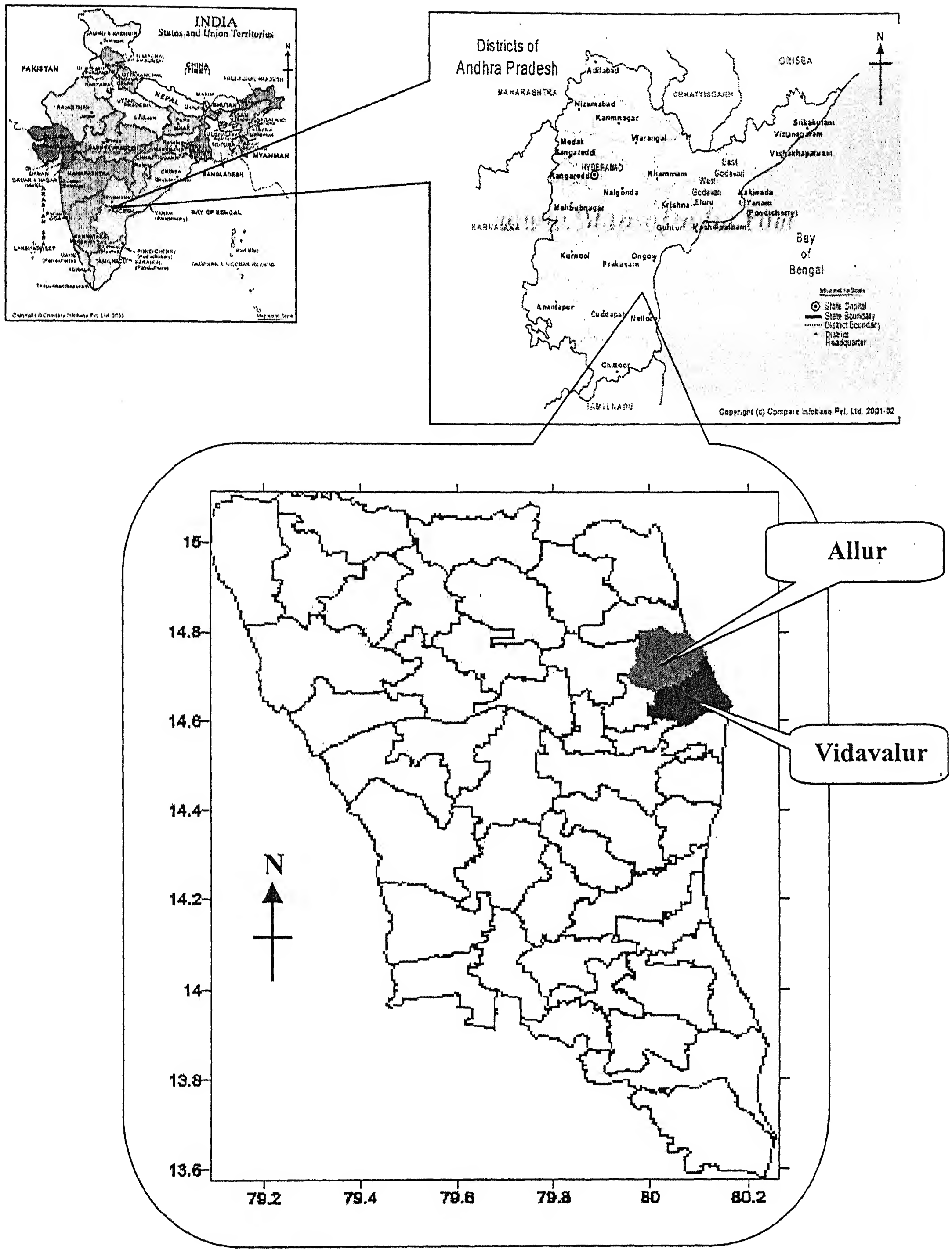


Figure 3.1 Geographical location of Study area

(Source: http://mapsofindia.com/maps and Groundwater dept., Nellore)

3.3 Hydrogeology of the study area

Groundwater occurs in almost all the geological formations of the district. However, its potential depends upon the nature of the geological formation, geographical set up, incidence of rainfall, recharge and other hydrogeological characteristics of the aquifer of the area. Hydrogiologically the district is classified as consolidated, semi consolidated and unconsolidated.

The present study area comes under unconsolidated formations. These formations area formed by deltaic alluvium due to Pennar, wind blown sands and coastal alluvium along the coast and in inter deltaic areas. These alluvium formations consist of admixtures of sand, silt and clay and form a multilayered aquifer.

The saltwater intrusion is already occurring in this area. This is mainly due to excess withdrawal of groundwater for domestic, agriculture and aquaculture. For the past 5 years the growth of aquaculture industries is very high, which requires huge amount of water. The only source in this area is groundwater. The observation data by State Groundwater Department, Nellore suggest that water the table is going down every year. In addition to high pumping, there is no good amount of rains for the past 4 years (2001-2004). This further accelerates the groundwater detoriation. The only source of groundwater is recharged is through rainfall. The data collected for this study area are briefly described below.

3.4 Collection of Data

The data required for the saltwater intrusion study has been collected from various government organization of the Nellore district like State Groundwater Department, Chief Planning office, Mandal Revenue Offices (MRO) of both mandals

and the Water supply Departments. The sources of various types of data are briefly mentioned below.

State Groundwater Department:

- Monthly Piezometric levels over a period of time.
- General Pumping rates in the area.
- Village wise Draft for the year 2000, which is considered as initial time period.
- Elevations of terrain with respect to mean sea level.
- Some water quality (Chloride concentration) data.
- Aquifer Parameters.

Chief planning Officer, Nellore:

- Monthly Rainfall data over a period of time.
- Hand book of statistics for the year 2003-04, which includes many statistical information useful for this study.

Data from Water Supply Department:

- Water quality (Chloride concentration) data of the study area.

Mandal Revenue offices of Allur and Vidavalur

- Data regarding the number of bore holes, filter points and hand pumps.

3.5 Description of data

No department has all the data required for this study, so it was essential to collect the data from different sources. Some data or information was also collected through discussions with some of the retired persons who worked in that area.

The required input data for the coastal aquifer flow and transport simulation model are head, concentration, pumping rates, boundary conditions, type of soil layers and their thicknesses below the study area, hydraulic parameters and rain fall data. Starting time period for this study is July 2000. Existing data were therefore collected for the period between 2000 and 20004. Some head and concentration data are missing for some portions of the time period between 2000 and 2004. Some data are abnormal, especially concentration data, so those outlayers are deleted. The details of the input data utilized in this study are explained below.

3.5.1 Head

There are 34 piezometers (Observation wells) present in Nellore district, 2 of them falls in the study area. Only 18 piezometers provide complete information. This is because, some of the piezometers doesn't have elevation levels with respect to mean sea level, some does not have water level data during the desired period and some piezometers are dismantled in between the required period in the process of some renovation works in those areas. Therefore, head values from these 18 piezometers are considered for interpolating the head values in the study area. The water levels are available with respect to ground level; these values were converted with respect to mean sea level.

Hydraulic heads respect to MSL in these 18 piezometers, are used to interpolate the heads for each of the years 2000 to 2004. Head contours were obtained for these interpolated head values. Specific points were located in these contours to assign head values as input to the simulation model. Later, the contours of 2001 and 2002 are used for calibrating the model and 2003 & 2004 contours are used for validation of the model, in terms of simulated hydraulic heads.

3.5.2 Chloride Concentration

Chloride concentration data are not available for all the required period and the available data are not covering the entire study area. Chloride concentration data are collected from State Groundwater Dept., Nellore and Water Supply Dept. The quality data are not strictly maintained.

Some of the quality data in the same locality is very abrupt; such outlayers are not considered due to lack of reliability. Year 2000 quality data are taken as the initial concentration for the simulation model. Concentration of year 2001 is used for calibration and year 2002 & 2003 quality data are used for validation of the model.

3.5.3 Wells and Pumping Rates

The study area consists of various types of wells for withdrawing groundwater for various uses. Generally the area covers dug wells, bore wells, hand pumps and filter points. Filter points are dominating in this area. Depth of filter point wells vary from 6 to 30 m, however in most cases the depth vary between 6 and 11m. The exact number of wells is not available in this region. Information on the drafts for the year 2000 is available.

One of the most difficult information to obtain is the withdrawal of draft from each known pumping well. The estimates are generally unreliable, and may miss some withdrawals. In this study, the groundwater draft for the year 2000, as provided by the State Groundwater Department has been increased by 10% to reflect this. This estimate is used as the pumping rate for the year 2000. As the draft values for the subsequent years are not available, pumping rates for subsequent years are increased by 25 % of the previous pumping rates, to reflect the increasing trends of total pumping in this area.

3.5.4 Statigraphical Data

Sufficient data to determine the geological stratification below the ground surface in this study area is not available, as lithological studies were not conducted in this area. But the thicknesses and type of the soil layers are specified based on the lithological data of the near by areas. This study area generally falls under alluvium type of soils which are generally admixtures of sand, silt and clay. In the simulation model that was used o simulate the coastal aquifer processes, three layers are considered. First layer below the ground surface is sand, of about 12m thickness, followed by sandy clay of about 3m thickness, followed by sand of 15m thickness. The entire multilayered system considered as heterogeneous and anisotropic.

3.5.5 Boundary conditions

The selected area is bounded by Bay of Bengal on east side, by Penna River in the south direction. Artificial Political (Mandal) boundaries are considered in north and west directions as shown in the figure 3.1.

Using these data a three-dimensional finite element model is implemented using the numerical model FEMWATER to simulate the flow and transport processes in the aquifer. Since the data are not adequate to reproduce all the true conditions of the field, the three-dimensional finite element model some necessary assumptions are made which are explained in the next chapter. This collected data are utilized for implementing the numerical model for simulating the aquifer system.

Chapter 4

Implementation of the numerical Simulation Model

Chapter 4

Implementation of the Numerical Simulation Model

4.1 Introduction

The collected data from various sources are utilized for developing and implementing the 3D finite element simulation model in FEMWATER. The calibration of the model for the study area is done in two steps. The simulation model is first calibrated with respect to the hydraulic heads only, using the flow model. Once, the calibration with respect to the flow model is found to be satisfactory, the calibration of the model is carried out for both the flow and transport processes. This model simulates the saltwater intrusion process as coupled flow and transport process.

Therefore, the first step calibration is only for approximation of the hydraulic parameters and boundary conditions. Hence, it is assumed that satisfactory calibration can be achieved only by considering the coupled flow and transport processes. Following satisfactory calibration of the coupled flow and transport process in terms of spatial and temporal observed hydraulic heads and salt contamination, validation of the calibration process was also carried out. After calibration and validation, the model is utilized for predicting the future saltwater intrusion scenario for the existing withdrawal pattern and for specified withdrawal scenarios or strategies aimed at controlling the saltwater intrusion. Input data and calibration procedure are explained in this chapter. The units system used in this model is shown in table 4.1.

Table 4.1: Unit system considered in the model

Item	Unit
Length	m
Time	year
Mass	kg
Force	N
Concentration	mg/l

4.2. Assumptions

The available data are not adequate for this study; more over all the required data are not available with any single departments. Even some of the available data are erroneous, and some other essential data are not available. Therefore it was necessary to make certain assumptions while implementing the 3 dimensional finite element models. The assumptions are

- Recharge rate in the form of infiltration is taken as 15% of the normal rainfall, in that particular period.
- The River boundary is assumed as no flow boundary, as the Penna River remains dry for most part of the year in this region.
- Seasonal fluctuations are not considered.
- Tidal affect is not taken into account.
- The pumping and recharge rates are averaged over the year, the total value is the total pumping occurring over the year.

4.3 Input data

The available data with some assumptions are used for assigning various input data for the model. They are briefly explained below

4.3.1 Boundary Conditions

The study area is bounded by the sea in the east. The Penna River forms the southern boundary. The rest of the study area is bounded by administrative boundary or the mandal boundaries.

The coastal boundary is defined as constant head (Dirichlet boundary) and constant concentration boundary, in which both the head and concentration are constant over time. In the model, for this boundary, the specified head is taken as zero (MSL) and specified concentration as 2400mg/l. The river boundary on south is taken as no flow boundary since the river is almost dry for the past 5 years. The mandal boundaries are considered as variable flux boundaries. Concentrations are specified as boundary condition only at the sea face.

4.3.2 Pumping and recharge rates

The pumping rates are assigned in such a way that the total pumping from all the wells in a village is equal to the total estimated draft of that village. Pumping rates are then estimated for the year 2000, as these quantities are available only for this year. It is assumed that an increment of 25% each year over the previous year would be reasonable estimates of the pumping rates for the period between July 2000 and July 2004. The recharge rate in the form of vertical infiltration is taken as 15% of the

normal annual rainfall. The locations of the wells and boundaries of the selected study area are shown in figure 4.1.

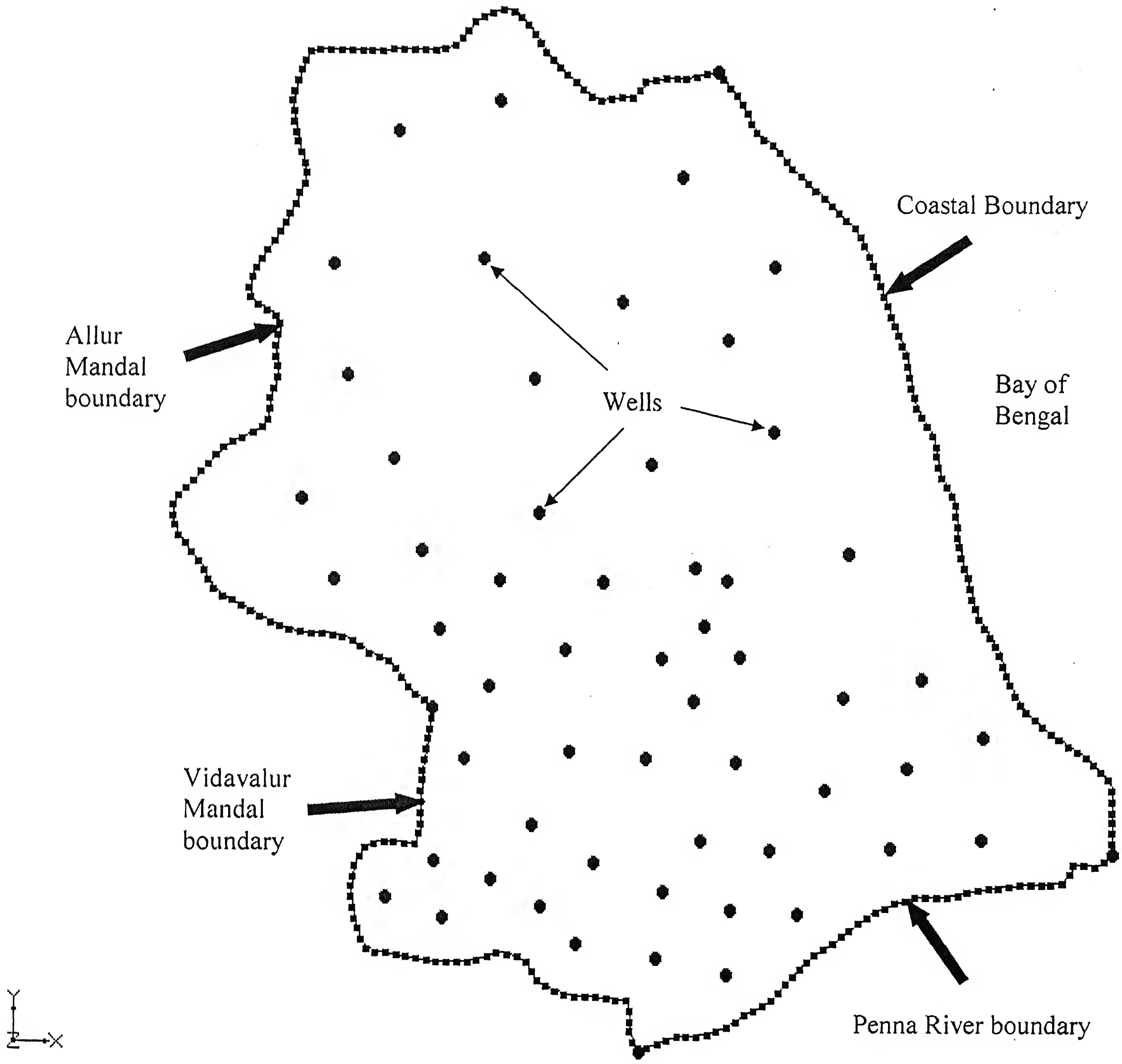


Figure 4.1: Plan view of study area with boundaries and well locations.

4.3.3 Head and Concentration

Initial head and concentration values are specified for each and every node of the 3D finite element model. In the present study, July 2000 is taken as beginning of the first time period. Both the head and concentration values in July 2000 are assigned to each and every node of the model, as initial conditions.

4.3.4 Fluid Properties

The fluid properties needed to be specified are density of water ($\rho_o = 1000$ kg/m^3), dynamic viscosity of water ($\mu_o = 280985.76$ kg/ m*yr), compressibility of water ($\beta = 4.71e\text{-}026$ m*yr^2/kg) and dimensionless density reference ratio ($\varepsilon = 0.025$)

4.3.5 Hydrogeological Parameters

Hydrogeological parameters like Hydraulic conductivity, compressibility of the medium, etc. are necessary for calibration of the simulation model. For the unsaturated zone, moisture content, relative conductivity and water capacity curves are automatically generated by the model for specified type of material present in each layer.

Using all above input data the model is first used for simulating the flow conditions, subsequently, after approximate calibration the model is used for simulating coupled flow and transport condition. The calibration processes is carried out for the time period between July 2000 and July 2002. The simulated and observed head and concentration values area compared for July 2001 and July 2002. The model is then validated for July 2003 and 2004, mainly in terms of head values, as estimated data are

very scanty for 2003 and non existent for 2004. The calibration model is then utilized for predicting the future scenarios for various pumping patterns. The calibration of flow and coupled flow and transport models are explained below.

4.4 Simulation of flow and transport model

The 3 dimensional finite element based flow and transport simulation model for coastal aquifers, FEMWATER is used as the simulation model. The total number of nodes and elements of the model are 37080 and 60165 respectively. The 3D model consists of three layers. First, sand layer of 12 m thickness. Then, sandy clay layer of 3m thickness followed by sand layer of 15m thickness. The different layers of the model are shown in the figure 4.2. Different views of the modeled study area are shown in figures 4.3a, b & c. The simulation is carried out for 2 years, starting from July 2000 with a constant time step of 0.04 yr. (14 days).

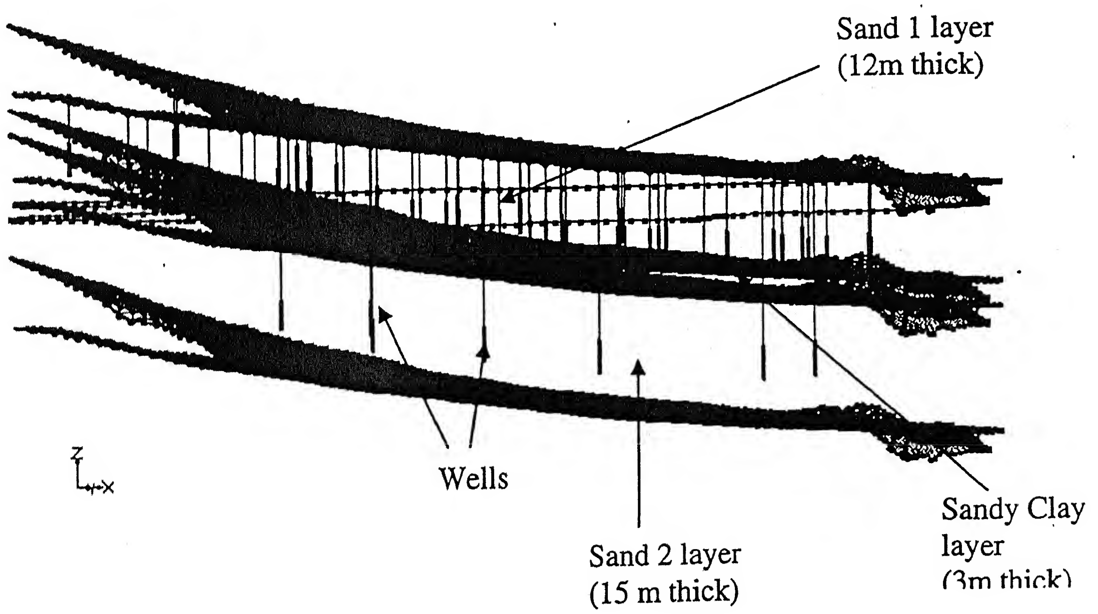


Figure 4.2 Geological Stratification of the Study area

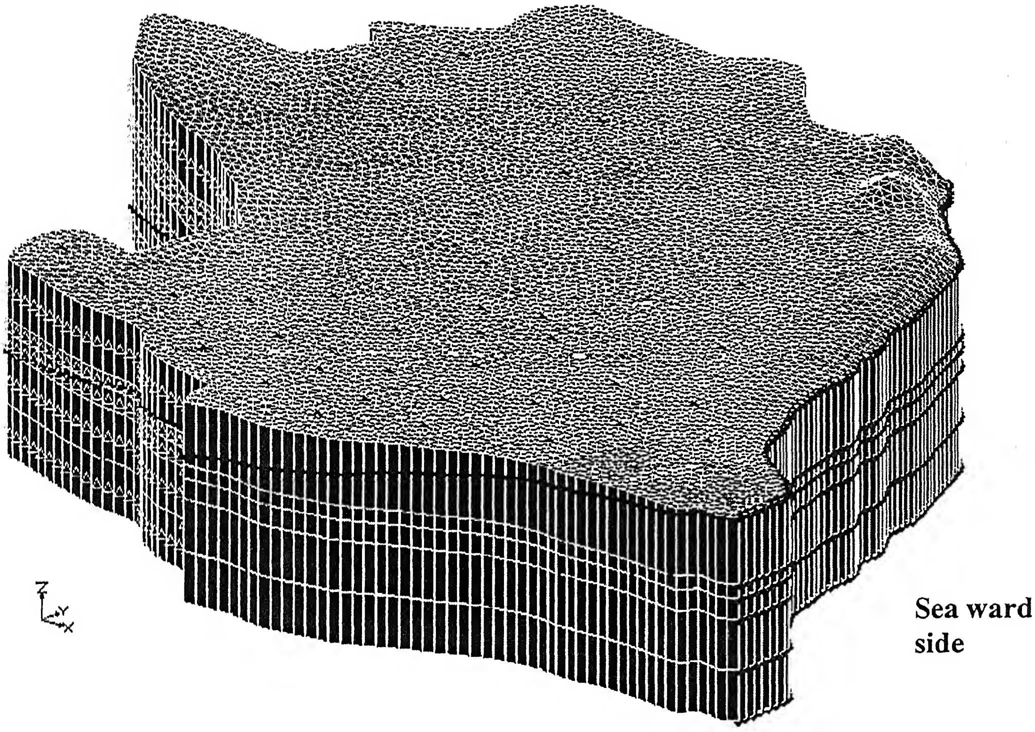


Figure 4.3a: Oblique 3D view of the study area

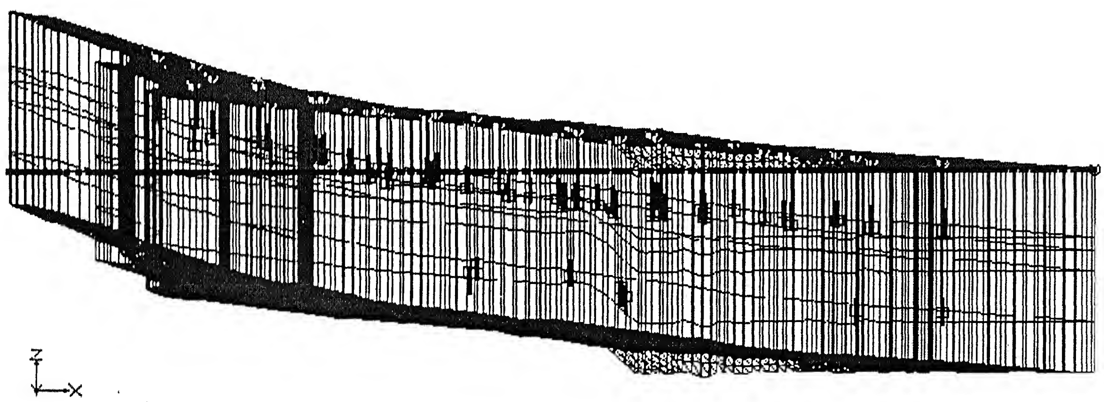


Figure 4.3b: Front 3D view of the study area.

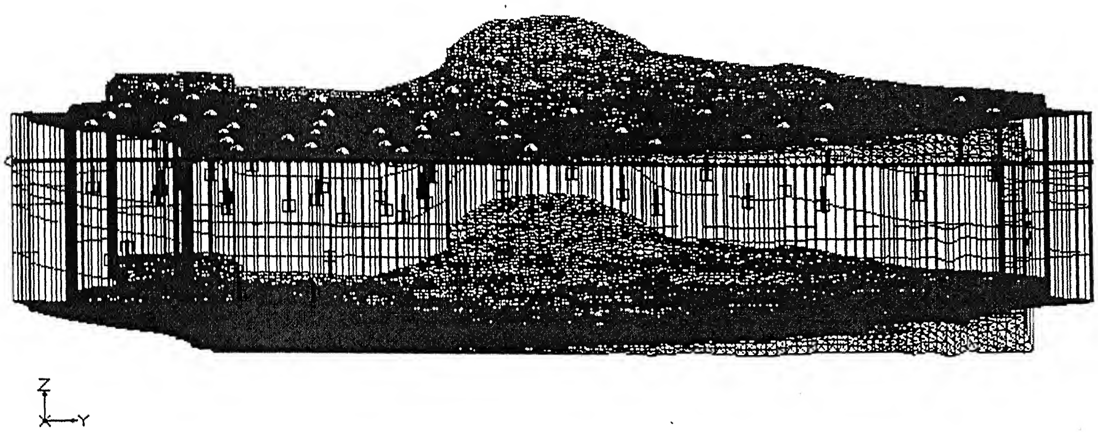


Figure 4.3c: 3D Side view of the study area.

4.4.1 Input data for transient flow and transport model

The input data for this transient flow and transport model is given below.

Boundary conditions: Boundary conditions are same as explained above.

Pumping Rates: The pumping rates are calculated from the village wise draft for the time period between July 2000 & July 2001.

Recharge rate: 0.1 m/ yr.

Head: Initial head values to each node are assigned by considering head contours for July 2000, which is obtained by interpolating the Piezometric head data with respect to MSL.

Concentration: Existing concentrations as on July 2000 are assigned to every node. For the nodes along the coast line a constant concentration of 2400 mg/l are assigned.

Fluid Properties: Density of water $\rho_O = 1000$ kg/m^3,

Dynamic viscosity of water μ_O =280985.76 kg/m*yr

Compressibility of water $\beta = 4.71e\text{-}026$ m*yr^2/kg and

Dimension less density reference ratio $\varepsilon = 0.025$.

Material Properties: For Sand

Hydraulic conductivity in x- direction, $K_{xx} = 3650$ m/yr

Hydraulic conductivity in y- direction, $K_{yy} = 3650$ m/yr

Hydraulic conductivity in z- direction, $K_{zz} = 1825$ m/yr

Compressibility of the medium, $\alpha = 1.0e\text{-}022$ m*yr^2/kg

Longitudinal dispersivity, $\alpha_L = 50$ m.

Lateral dispersivity, $\alpha_T = 15$ m.

Soil Porosity, $n = 0.3$

Bulk density of the medium, $\rho_b = 1200$ kg/m^3

For sandy clay

Hydraulic conductivity in x- direction, $K_{xx} = 150$ m/yr

Hydraulic conductivity in y- direction, $K_{yy} = 150$ m/yr

Hydraulic conductivity in z- direction, $K_{zz} = 75$ m/yr

Compressibility of the medium, $\alpha = 1.0e\text{-}021$ m*yr^2/kg

Longitudinal dispersivity, $\alpha_L = 50$ m.

Lateral dispersivity, $\alpha_T = 15$ m.

Soil Porosity, $n = 0.3$

Bulk density of the medium, $\rho_b = 1000$ kg/m^3

With the above input data, the transient flow condition is simulated for the two year period between July 2000 & July 2002. The result of the simulation is spatial heads at each time step (0.04 yr). The transient flow convergence criterion is 0.01m.

4.4.2. Calibration and validation of flow and transport simulation model.

The 3 dimensional finite element model simulates the spatial and temporal values of the hydraulic head. To calibrate the model with respect to heads, the simulated heads are compared with the observed heads at the end of 1st and 2nd years (July 2001 and July 2002). These observation locations are chosen arbitrarily, distributed over the entire study area. About 32 observation points are created in the whole study area. For each of these observation points, calibration targets are assigned by considering an acceptable measure of deviation of simulated heads for the observed heads. The observed head are based on interpolation of the available spatial head observations. The components of the calibration targets are illustrated in the figure 4.4.

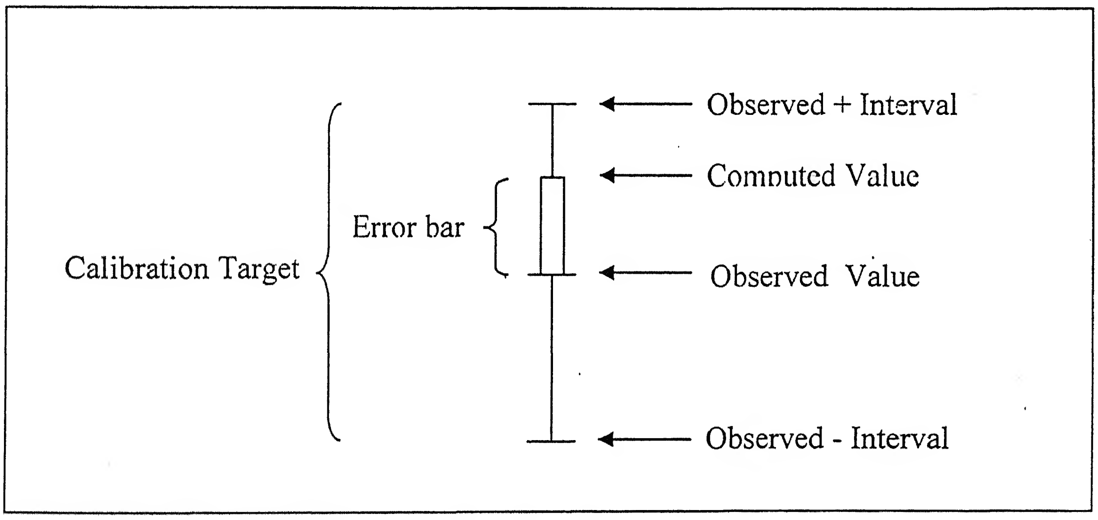


Figure 4.4: Components of calibration target

In the figure 4.4, the error bar quantifies the error between the observed head and simulated head. If the bar lies within the target the bar is in green color in the GMS out put. If it is shown in yellow the error is within 200%, and shown in red if it goes beyond this range. In this study an interval of 0.5m is specified, that means observed head +/- 0.5m is acceptable in the calibration stage. Figure 4.5 shows the locations of observed points.

The simulated hydraulic heads for different specified parameter values (hydraulic conductivity, recharge rate) were compared with the observed hydraulic heads as estimated by interpolation of observation data. The interpolation was necessary as the number of observation points were few in the study area. The spatial interpolation is based on observation data outside the study area as well. The pumping rates remain unchanged in calibration process as it is calculated from the observed draft initially, but hydraulic conductivity and recharge rates are adjusted to obtain simulated water levels which are satisfactorily match with observed heads.

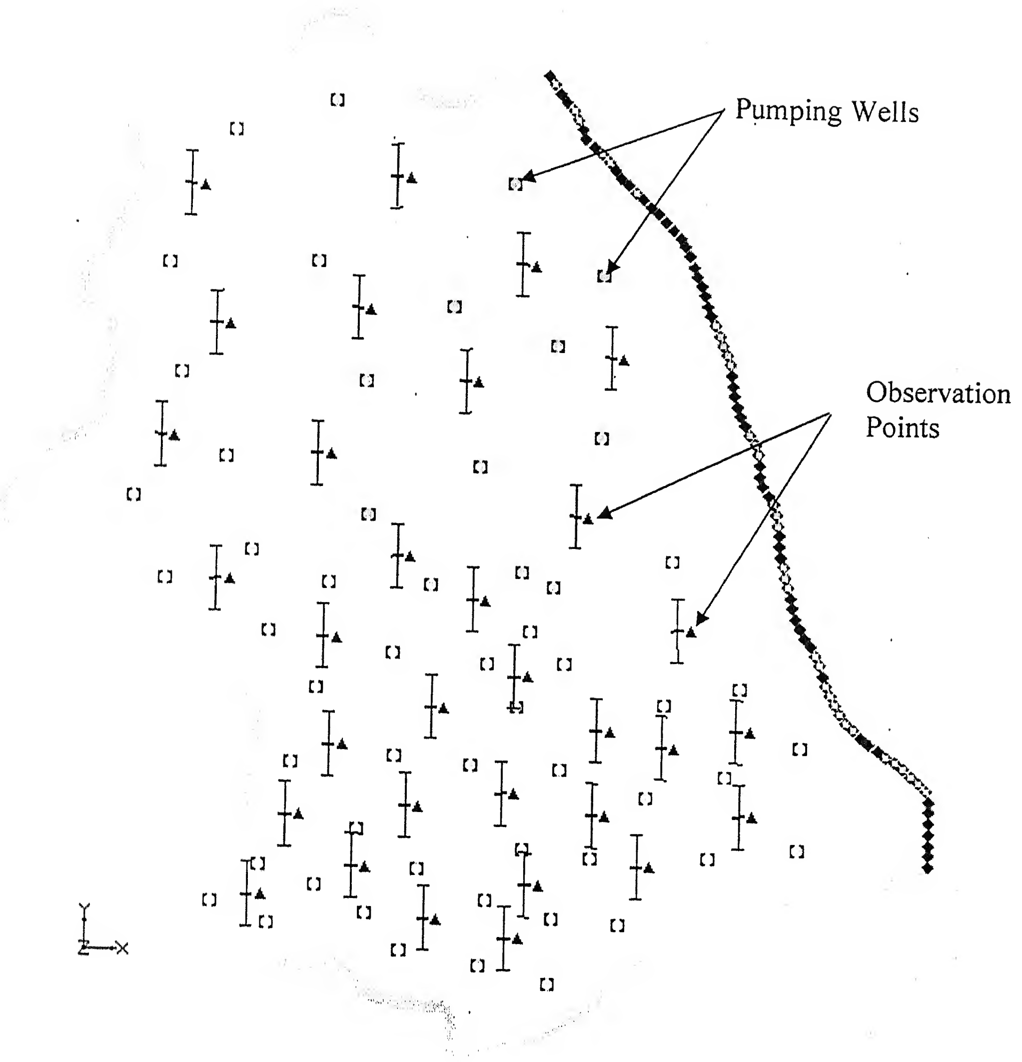


Figure 4.5: Plan view of study area with pumping wells and observation points.

Figures 4.6a and 4.6b show the calibration errors in terms of the hydraulic heads at the observation locations, on July 2001 and July 2002. These calibration results are for simulated heads for, K_{xx}, K_{yy}= 3650m/yr and K_{zz} = 1825 m/yr for sand and K_{xx}, K_{yy} =150 m/yr and K_{zz} = 75 m/yr for sandy clay, infiltration (recharge) rate of 0.1 m/yr. It is seen these error behavior observed and simulated heads are substantially exceeding the calibration target error of (+/- 0.5m).

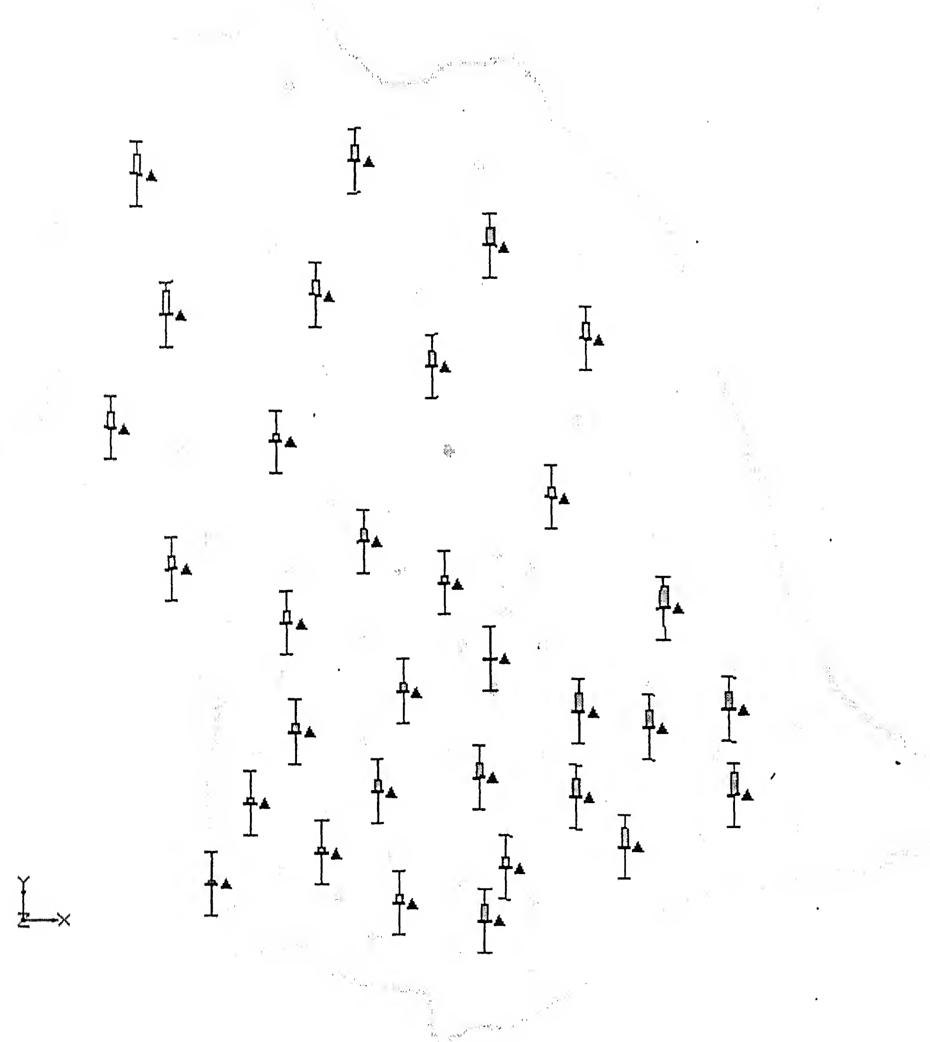


Figure 4.6a: Comparison between observed heads and simulated heads after one year, i.e. July 2001.

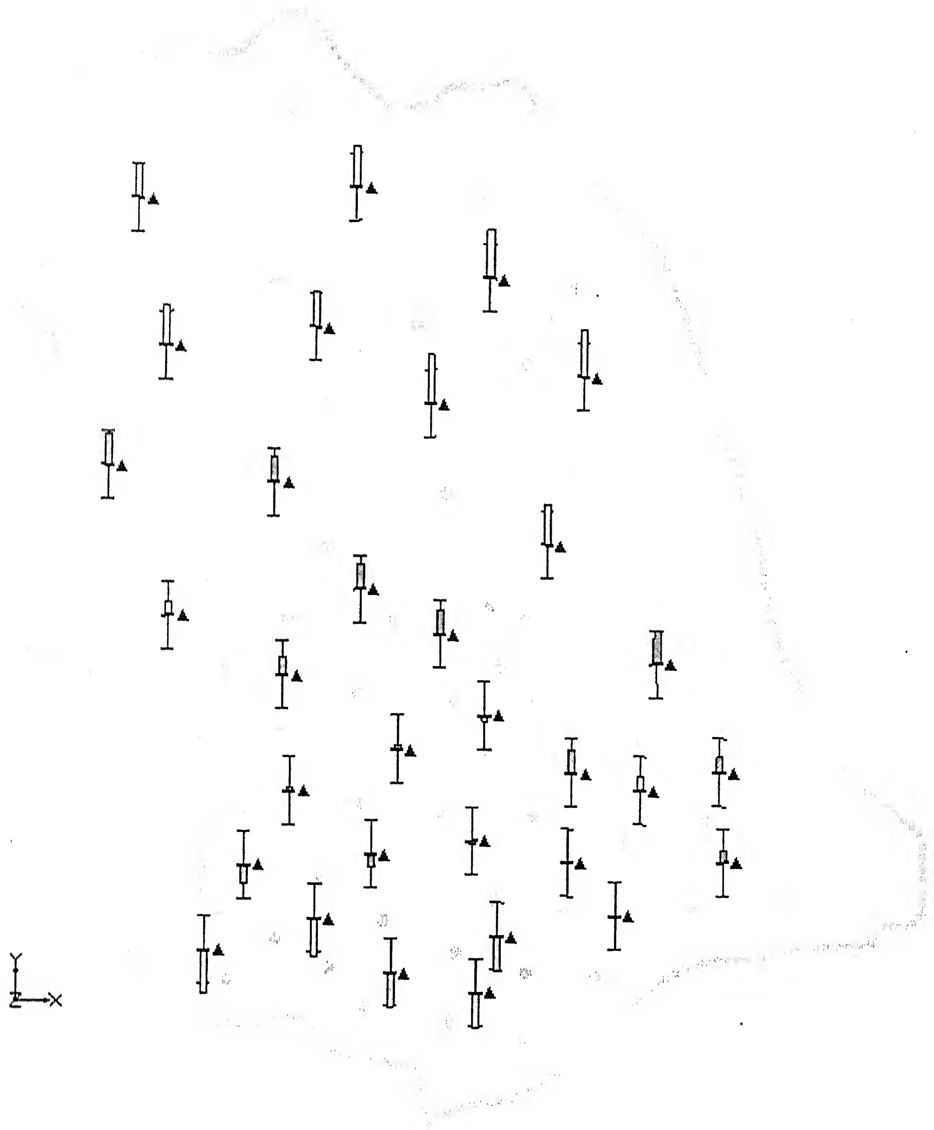


Figure 4.6b: Comparison between observed heads and simulated heads after second year, i.e. July 2002.

The calibration errors are smaller when K_{xx}, K_{yy}= 7300 m/yr and K_{zz} = 3650 m/yr for sand and K_{xx}, K_{yy} =180 m/yr and K_{zz} = 90 m/yr for sandy clay and infiltration (vertical recharge rate) is 0.2m/yr as seen in figures 4.7a and 4.7b. However, some of the simulated heads are beyond the specified calibration targets.

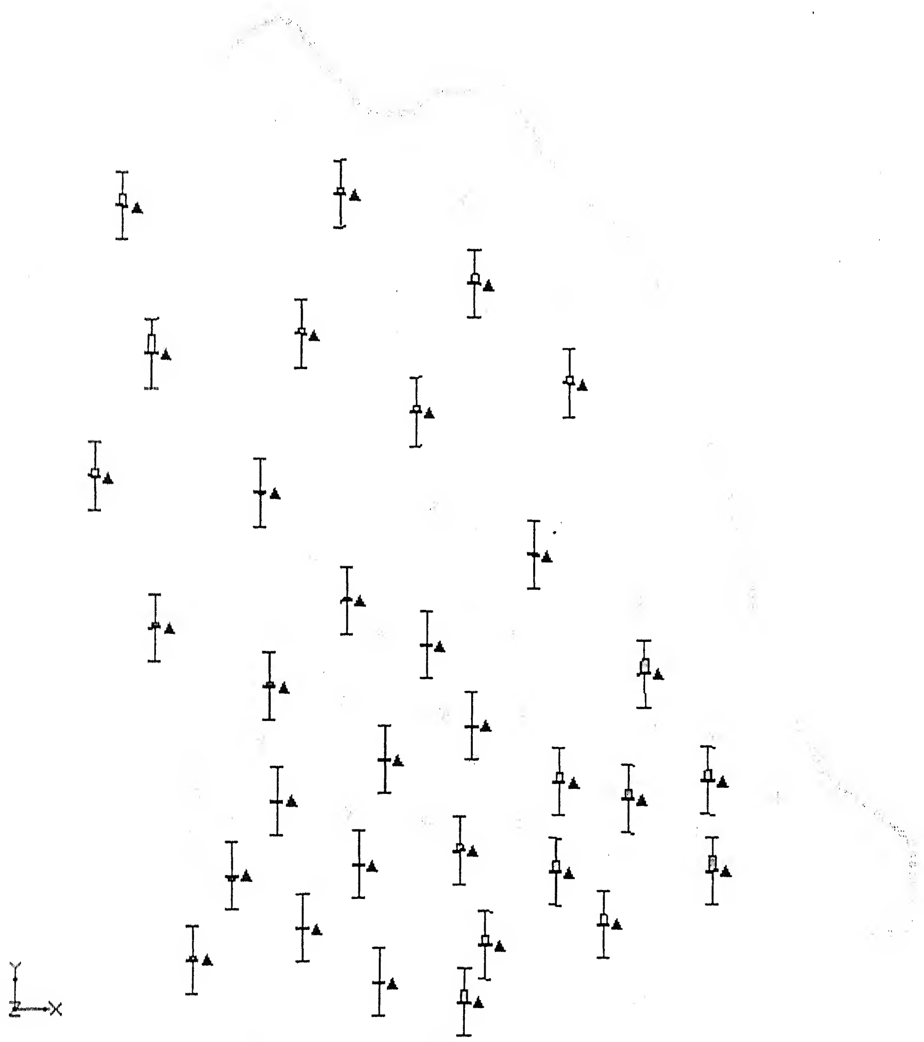


Figure 4.7a: Comparison between observed heads and simulated heads after one year, i.e. July 2001.

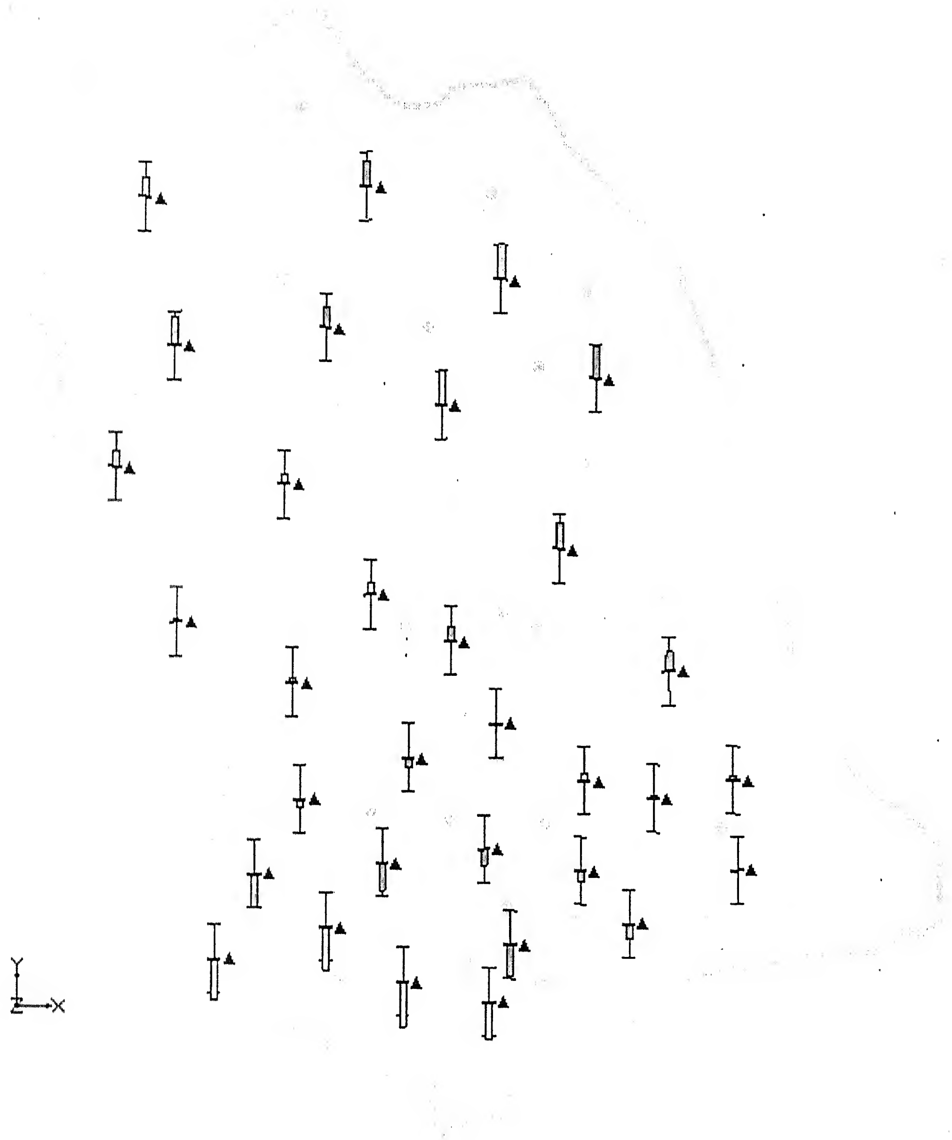


Figure 4.7b: Comparison between observed heads and simulated heads after second year, i.e. July 2002.

The value of K and the infiltration rate was further changed to K_{xx}, K_{yy}= 11000 m/yr and K_{zz} = 5500 m/yr for sand and K_{xx}, K_{yy} = 200 m/yr and K_{zz} = 100 m/yr for sandy clay and infiltration rate is 0.1m/yr. The calibration errors for July 2001 and 2002 are shown in figures 4.8a and 4.8b.

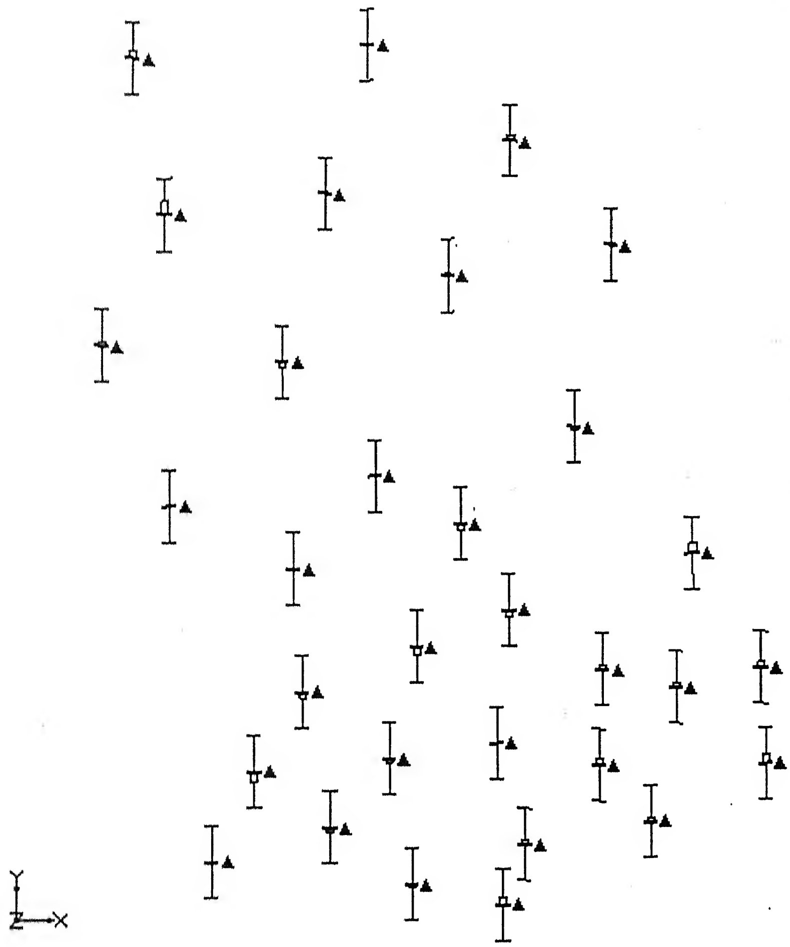


Figure 4.8a: Comparison between observed heads and simulated heads after one year, i.e. July 2001.

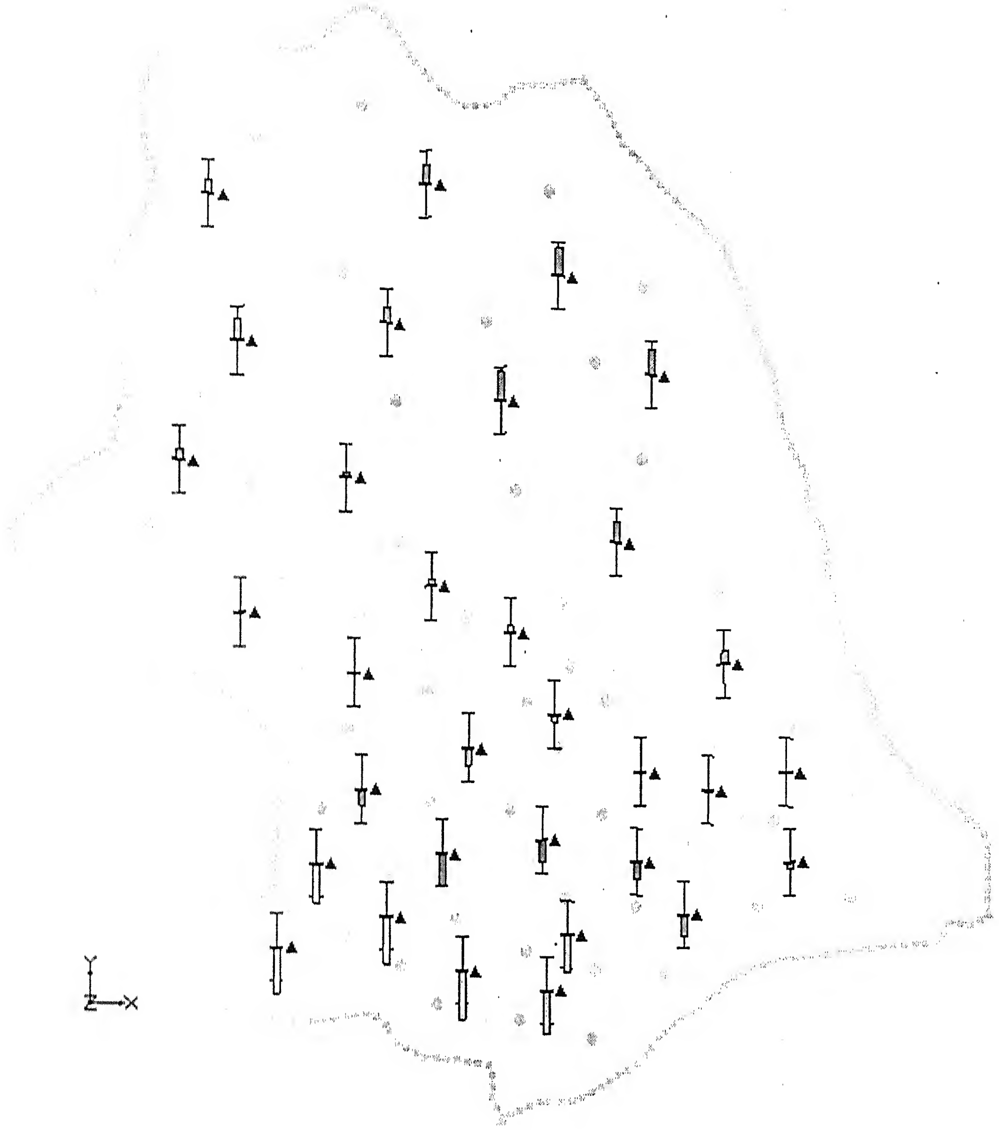


Figure 4.8b: Comparison between observed heads and simulated heads after second year, i.e. July 2002.

It is seen that the calibration errors are more or less within the acceptable error limit. Considering the inherent uncertainty in estimating the observed heads, and the reliability of the later, it was felt that these calibration results are acceptable. Minimizing the errors further, may not mean a more accurate simulation. The parameter values obtained by the trial and error process of model calibration are not

unique. The calibration process also leads to an understanding of the factors determining the system's response and behavior, that is, the parameters and boundary conditions to which the system is most sensitive. After observing the results of these simulations the best suited combination is K_{xx}, K_{yy}= 11000 m/yr and K_{zz} = 5500 m/yr for sand and K_{xx}, K_{yy} = 200 m/yr and K_{zz} = 100 m/yr for sand and a recharge rate of 0.1m/yr. The simulated hydraulic heads and the estimated observation heads were also compared over time for all the selected locations. These graphical comparisons are shown in figures 4.9 to 4.11.

Case 1: Hydraulic conductivity K_{xx}, K_{yy}= 3650m/yr and K_{zz} = 1825 m/yr for sand and K_{xx}, K_{yy} =150 m/yr and K_{zz} = 75 m/yr for sandy clay, infiltration (recharge) rate of 0.1 m/yr.

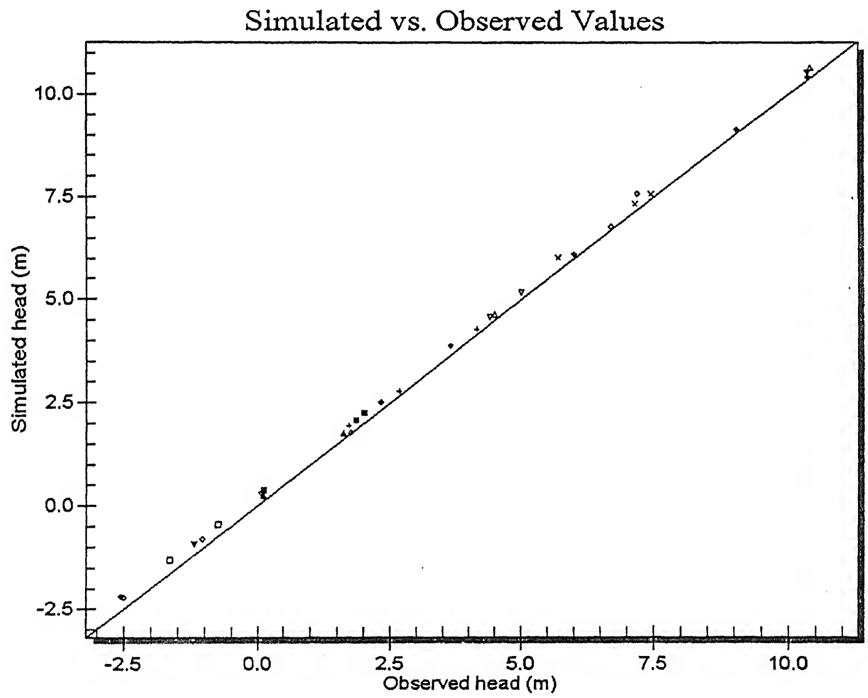


Figure 4.9: Simulated versus observed hydraulic heads. July 2001 (Case 1)

Case 2: K_{xx}, K_{yy}= 7300 m/yr and K_{zz} = 3650 m/yr for sand and K_{xx}, K_{yy} =180 m/yr and K_{zz} = 90 m/yr for sandy clay and infiltration (vertical recharge rate) is 0.2m/yr

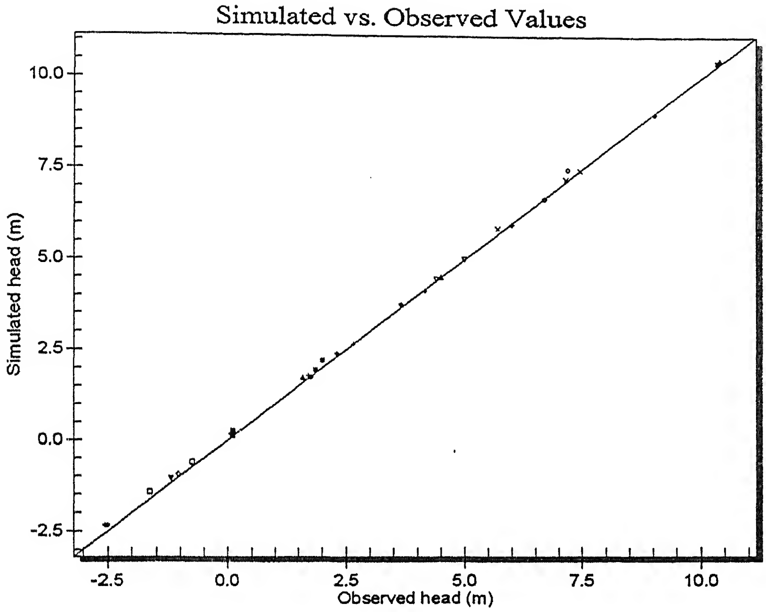


Figure 4.10: Simulated versus observed hydraulic heads. July 2001 (Case 2)

Case 3: K_{xx}, K_{yy}= 11000 m/yr and K_{zz} = 5500 m/yr for sand and K_{xx}, K_{yy} = 200 m/yr and K_{zz} = 100 m/yr for sand and a recharge rate of 0.1m/yr.

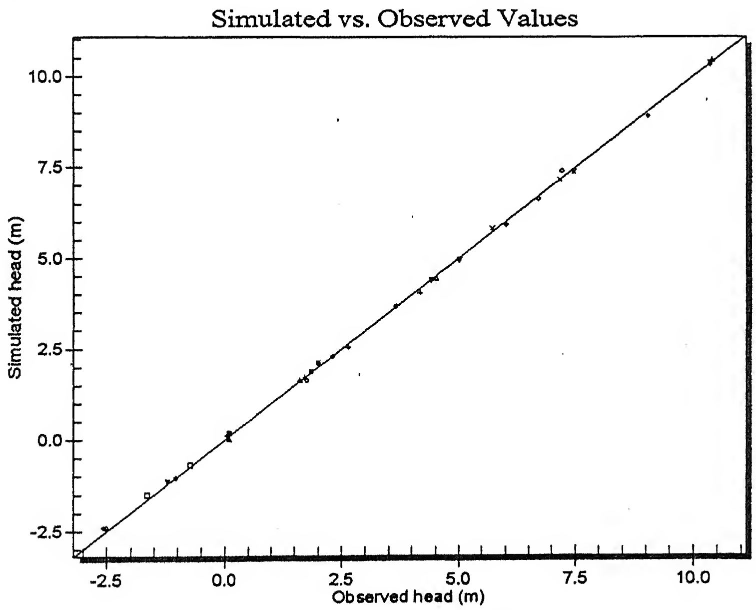


Figure 4.11: Simulated versus observed hydraulic heads. July 2001 (Case 3)

These graphs show that there is not much difference in errors in the above three cases. However, the parameter values specified for case 3 results in the best fit between observed and simulated heads. More over, with hydraulic conductivity values specified as 3650 m/yr and 7300 m/yr, some of the wells tend to dry up after some time. This problem also does not appear with case 3. Therefore, for further validation, these parameter values K= 11000m/yr and infiltration rate 0.1 m/yr are chosen.

Based on these chosen parameter values, and specified boundary conditions, the saltwater concentration is simulated using the coupled 3-D, transient, density dependent flow and transport simulation model. The salt concentration patterns over space and time, as simulated for July 2001, July 2002 and July 2003, and the observed concentration patterns for the same times are shown in figures 4.12 to 4.17. All these concentration values are based on the concentrations at the bottom of the top sand layer, in the 3- dimensional model.

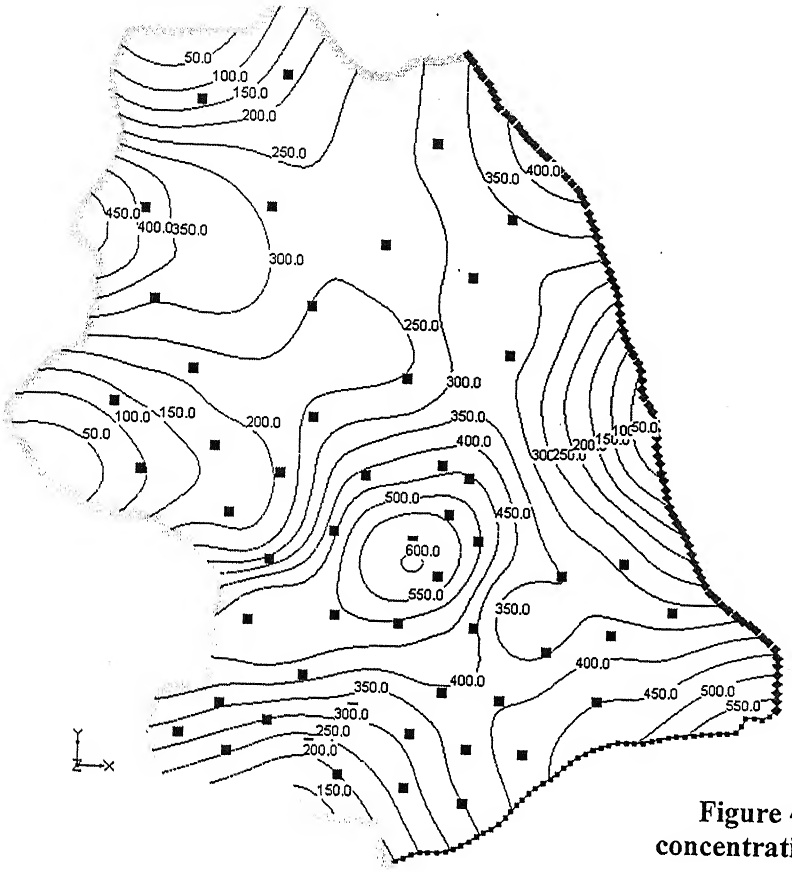


Figure 4.12: Observed salt concentration contours July 2001

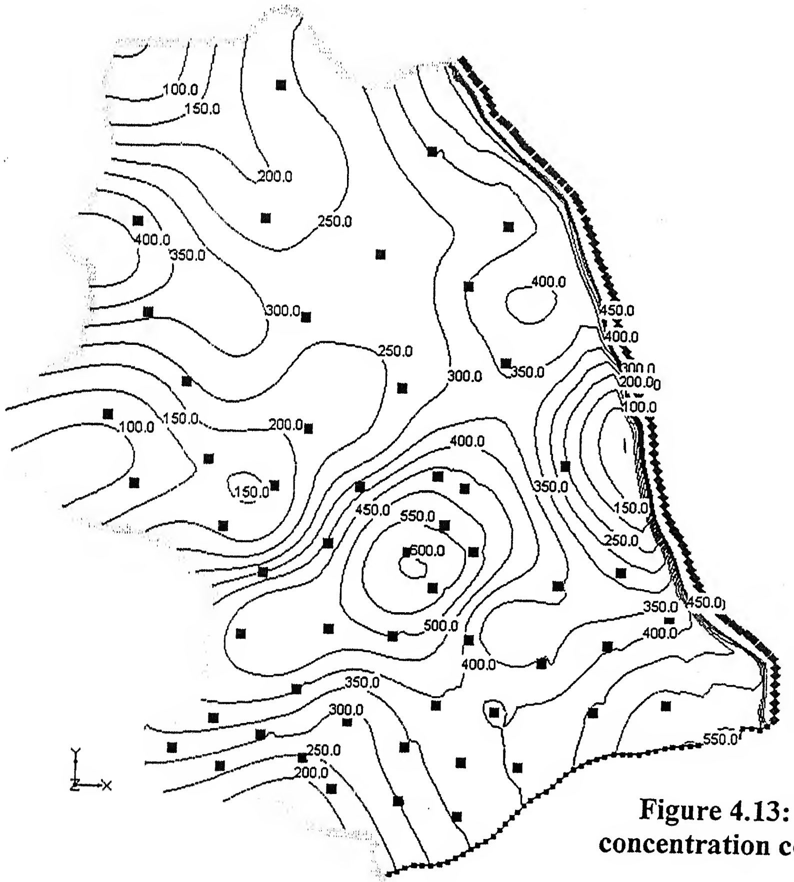


Figure 4.13: Simulated salt concentration contours July 2001

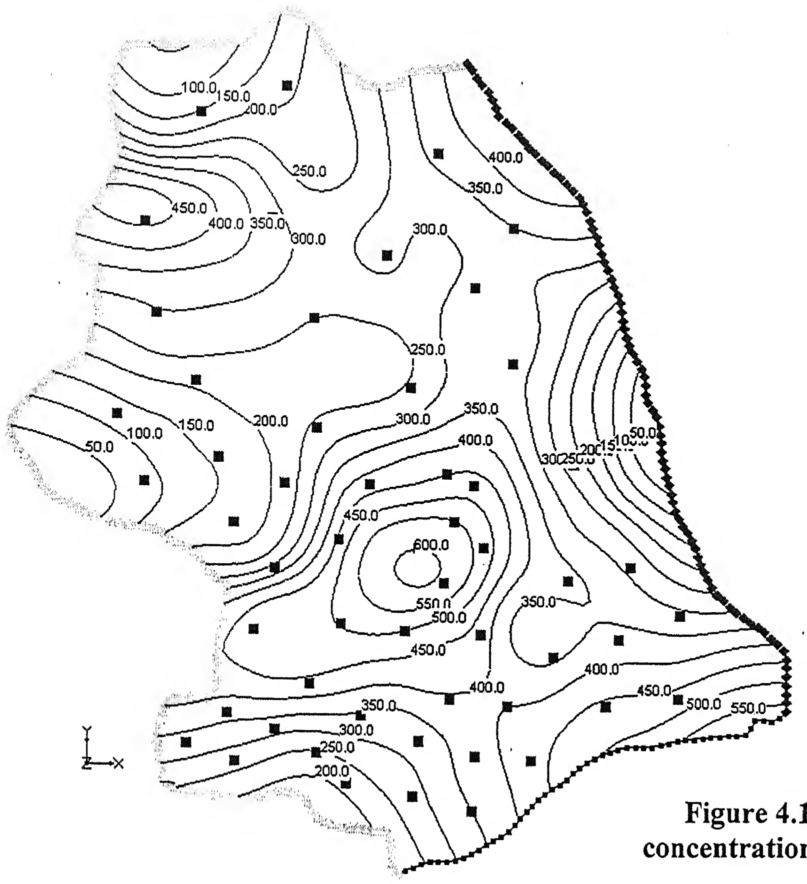


Figure 4.14: Observed salt concentration contours July 2002

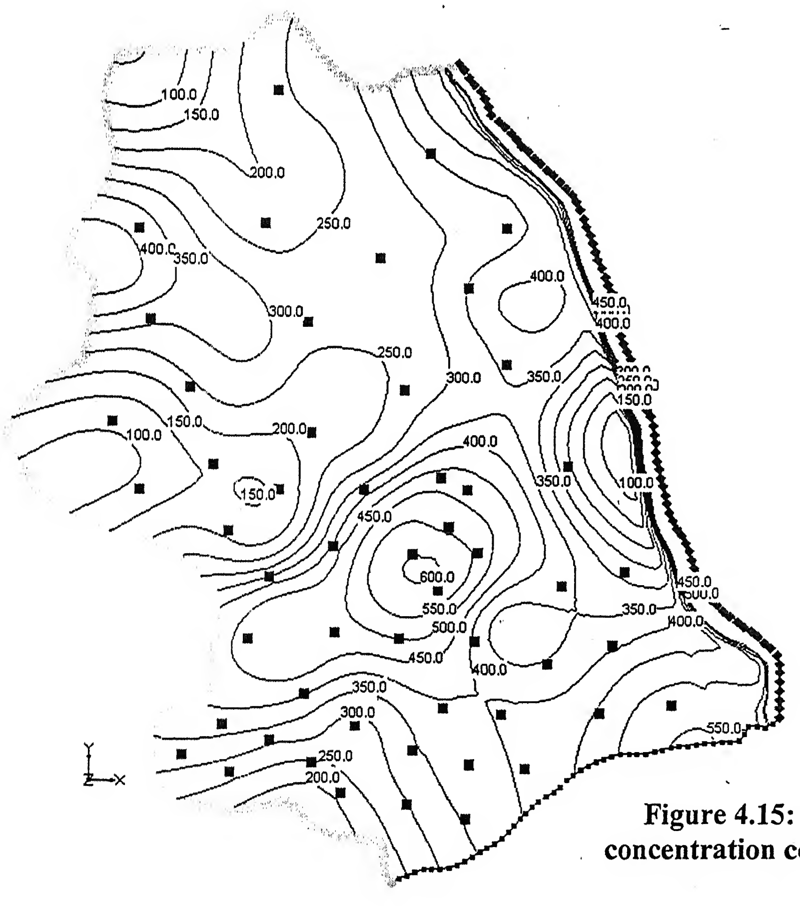


Figure 4.15: Simulated salt concentration contours July 2002

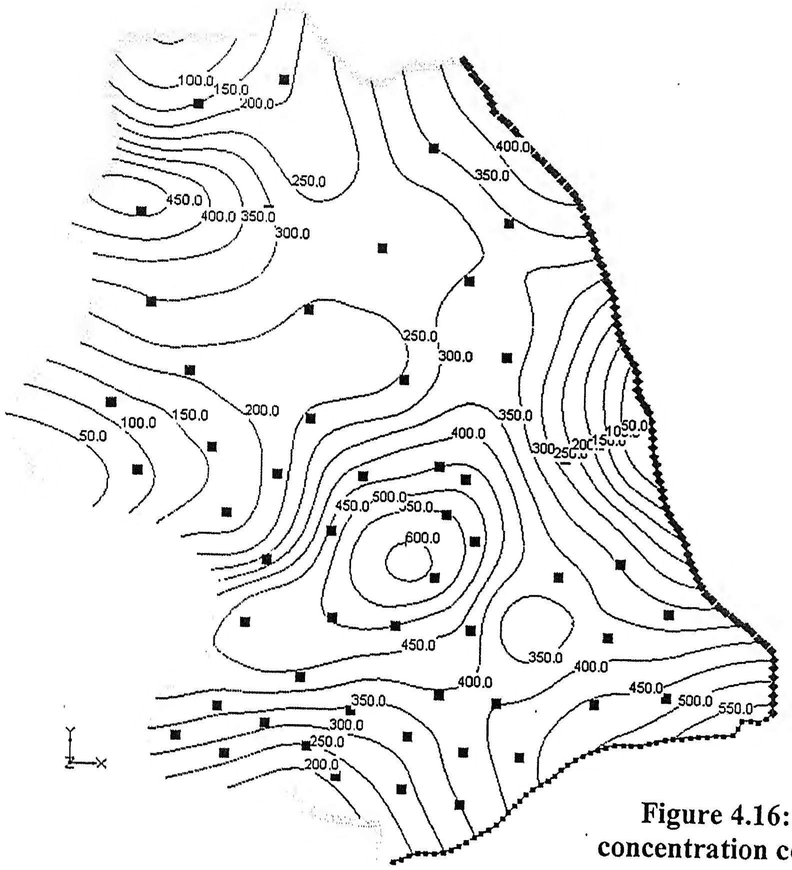


Figure 4.16: Observed salt concentration contours July 2003

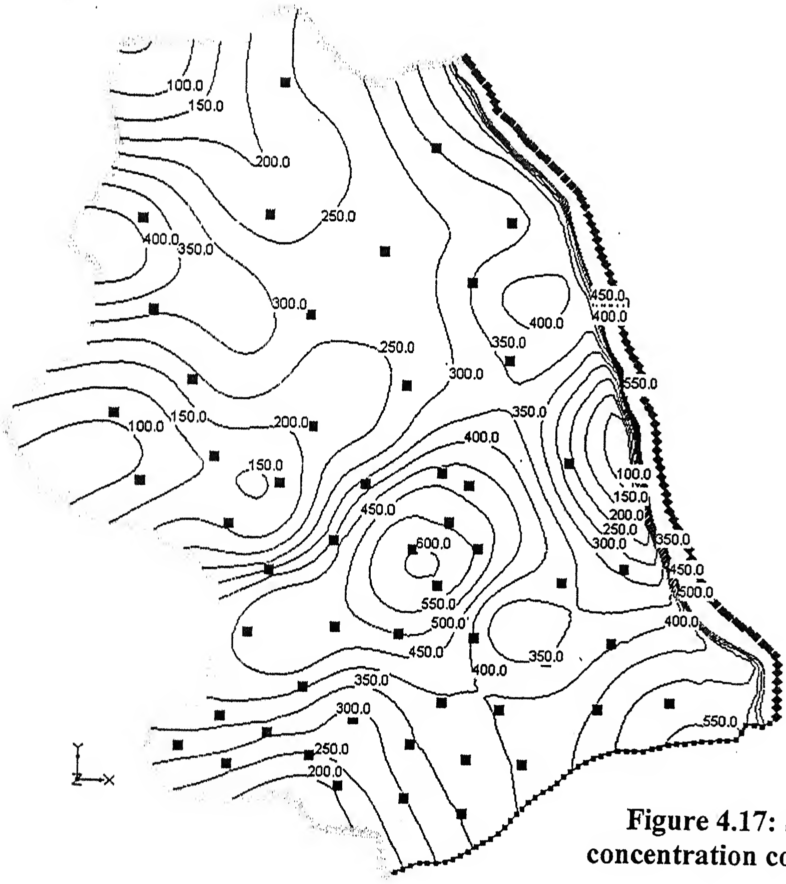


Figure 4.17: Simulated salt concentration contours July 2003

These figures show that the calibration model performs satisfactorily in simulating the salt concentration in the study area over the time horizon for which same observation data are available. Also the simulated hydraulic heads for July 2003 and July 2004 are compared with the estimated observed heads for validation of the calibration model. These comparisons are shown in figures 4.18 and 4.19.

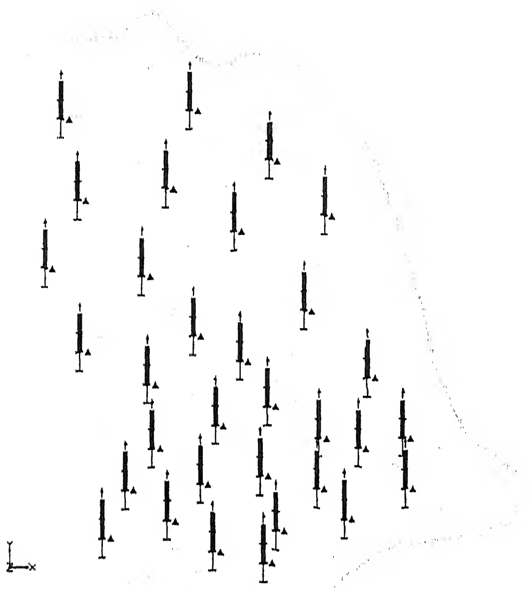


Figure 4.18: Comparison between observed heads and simulated heads after third year, i.e. July 2003.

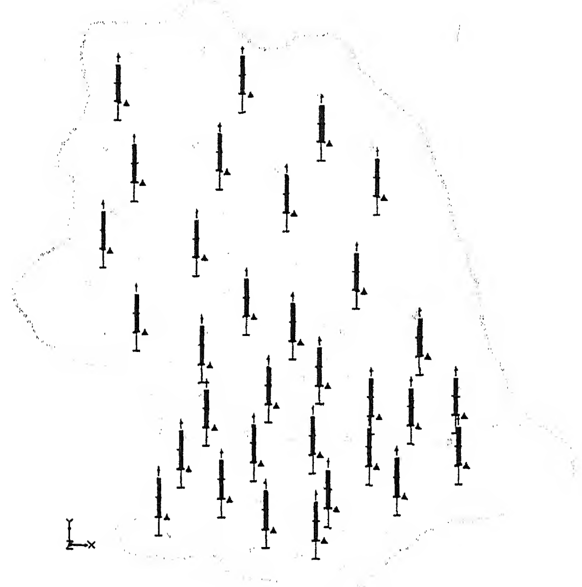


Figure 4.19: Comparison between observed heads and simulated heads after fourth year, i.e. July 2004.

These comparisons show, the hydraulic head simulation errors obtained using the coupled flow and transport model are within the acceptable range, considering the inherent uncertainties and errors in the scanty observation data available. This calibrated and partially validated simulation model is used to evaluate the effectiveness of few pumping or withdrawal scenarios on the saltwater intrusion process in the study area. These results are discussed in the next chapter.

Chapter 5

Results and Discussion

Chapter 5

Results and Discussions

The calibrated and partially validated simulation model is used to evaluate the effectiveness of few pumping or withdrawal scenarios on the saltwater intrusion process in the study area. To observe the response of the system, some extra wells are specified in a hypothetical scenario and the simulated results are compared with those for the existing. These scenarios are explained below.

5.1 Scenario 1: Additional pumping wells near coast in Utukuru village of Vidavalur Mandal (South of study area)

Additional pumping is assumed from five extra wells near the coast in the Utukuru village of Vidavalur Mandal. Figures 5.1a and 5.1b show the old and new pattern of the well locations respectively. The pumping rates are kept at 3,50,0000 m^3/yr for all additional wells specified in scenario 1.

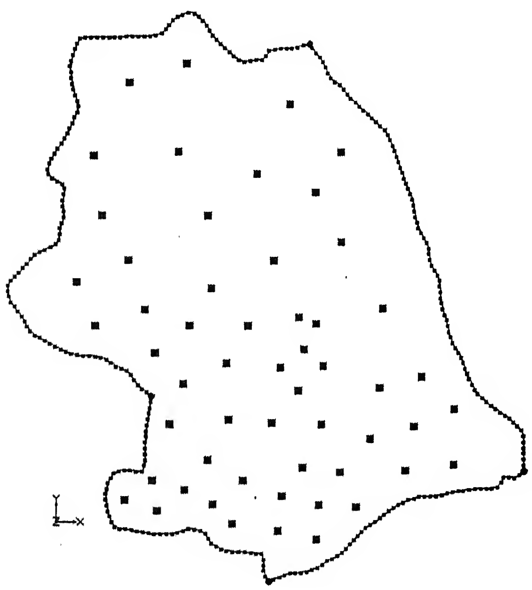


Figure 5.1a: Location of wells in existing old pumping pattern

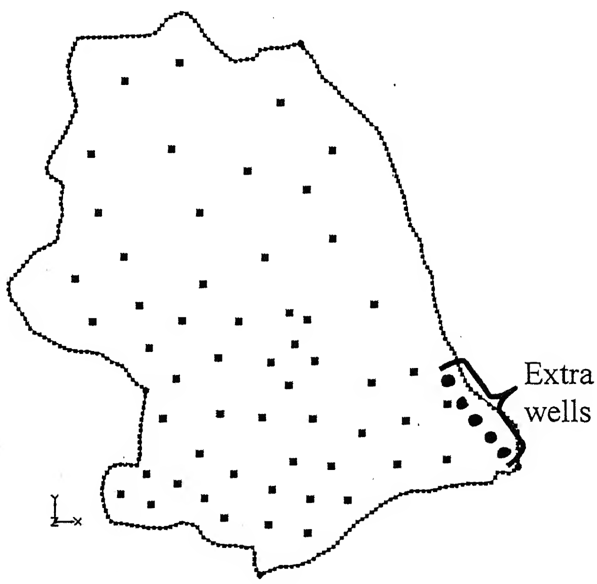


Figure 5.1b: Location of wells for new hypothetical pumping pattern (scenario 1)

The pumping in the new wells starts from the fifth year July 2005. Figures 5.2a and 5.2b show the concentration contours after five years from July 2004, i.e. in July 2009.

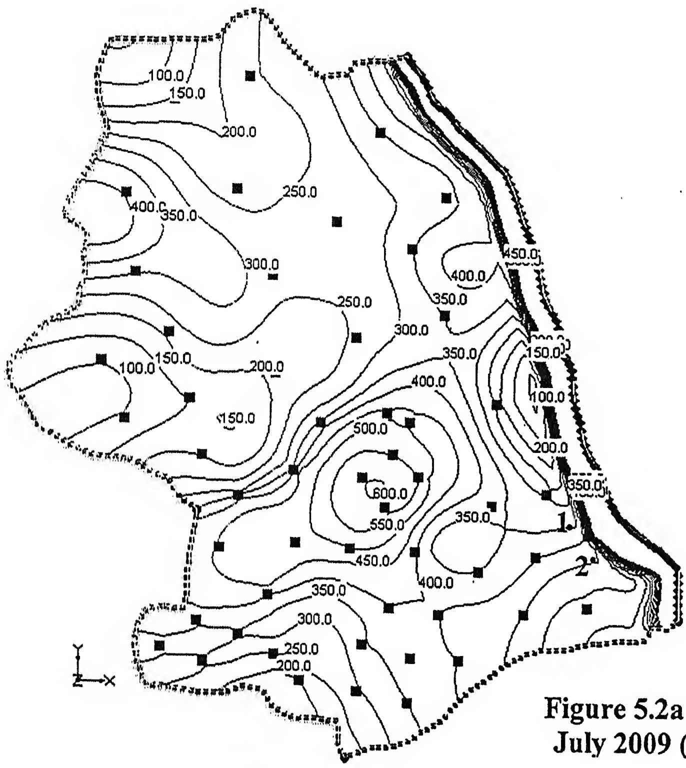


Figure 5.2a: Salt concentration contours in July 2009 (Existing old pumping pattern)

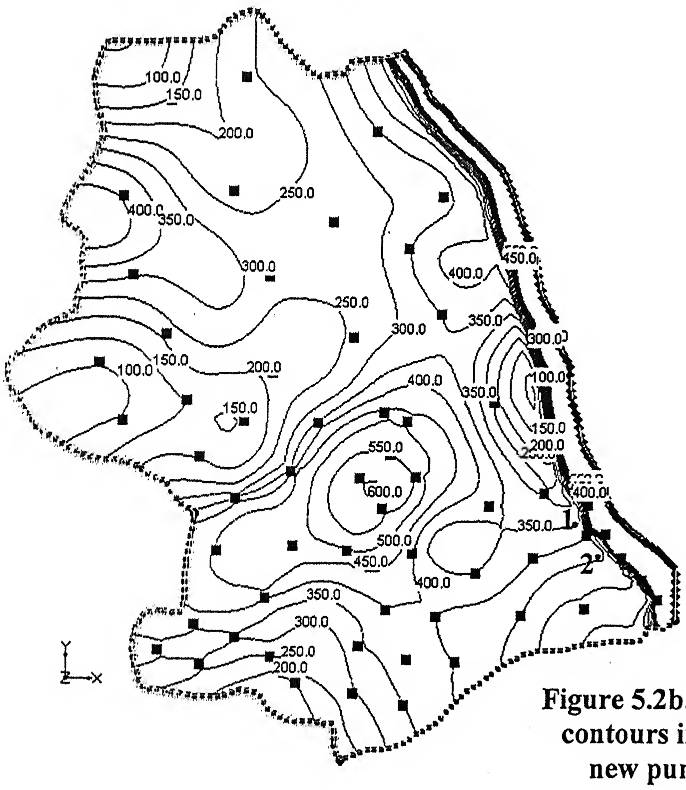


Figure 5.2b: Simulated salt concentration contours in of July 2009 (Hypothetical new pumping pattern, scenario 1)

It is observed from the concentration contours of July 2009, there is a decrement in salt concentration with extra wells in scenario 1. Figure 5.3 and 5.4 shows concentration variation with time for both the pumping patterns at two different specified locations 1 and 2.

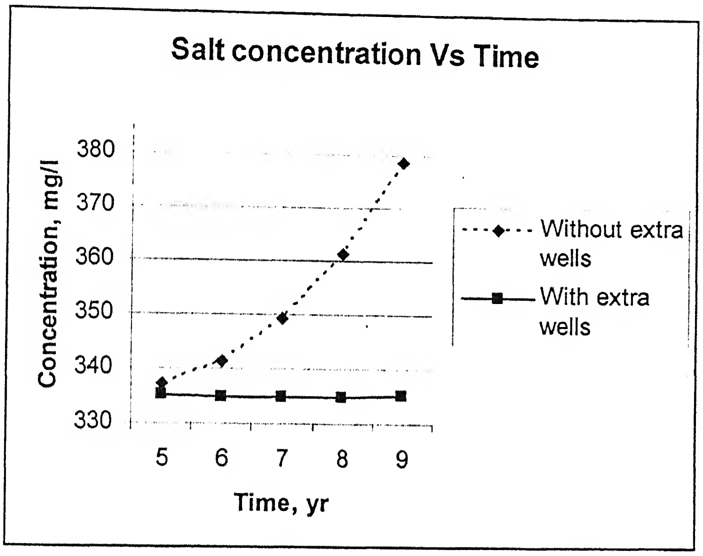


Figure 5.3: The concentration variation with time for both pumping patterns at location 1 (Scenario 1)

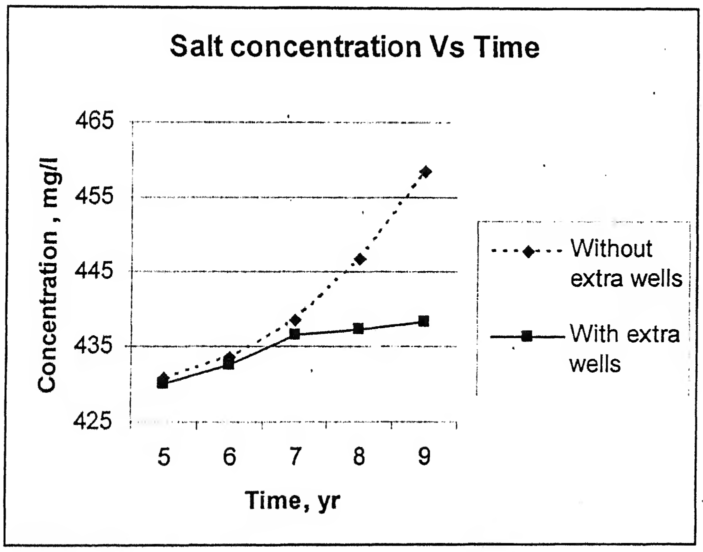


Figure 5.4: The concentration variation with time for both pumping patterns at location 2 (Scenario 1)

The lowering of salt concentration levels at locations, for which these values are shown in figures 5.3 and 5.4., is evident. Although only marginally, by inducing additional pumping at selected carefully chosen locations, it is possible to reduce the salt concentration levels at some other locations. Therefore it is possible to lower salt concentrations by careful planning of pumping patterns. This may improve groundwater condition in areas away from the coast line by controlling the saltwater intrusion.

5.2 Scenario 2: Additional pumping wells near coast line in Iskapalli village of Allur Mandal (East of study area)

Five extra pumping wells are hypothetically specified near the east coast line in Iskapalli village of Allur Mandal. Figure 5.5a and 5.5b shows the old and new pattern of the well locations respectively. The pumping rates in the additional wells are 3,50,0000 m^3/yr.

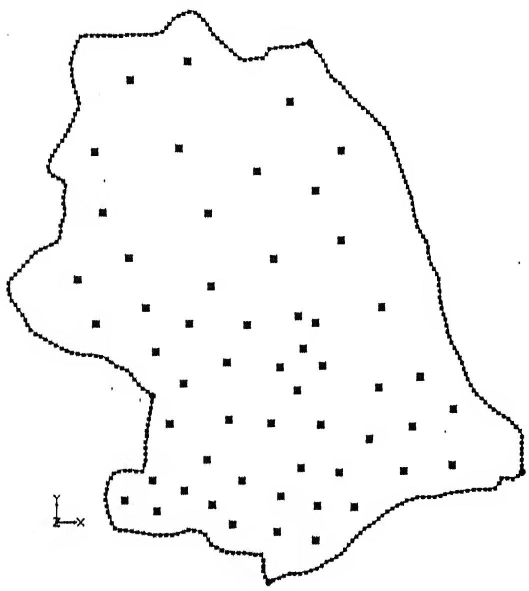


Figure 5.5a: Location of wells in existing old pumping pattern

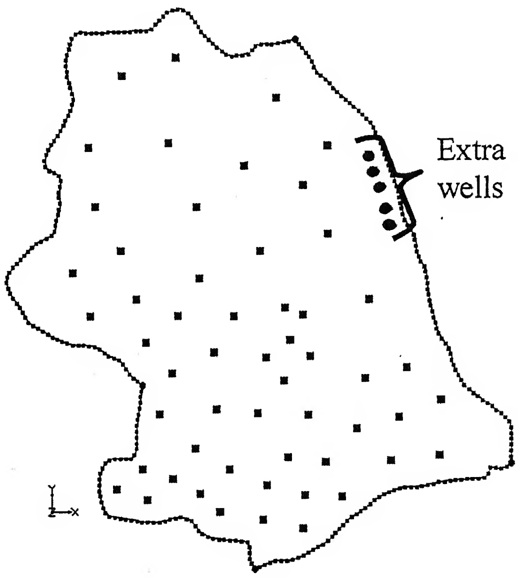


Figure 5.5b: Location of wells for new hypothetical pumping pattern (scenario 2)

The pumping in these new wells starts from the fifth year i.e., in July 2005. Figure 5.6a and 5.6b shows the concentration contours after five years from July 2004, i.e., in July 2009.

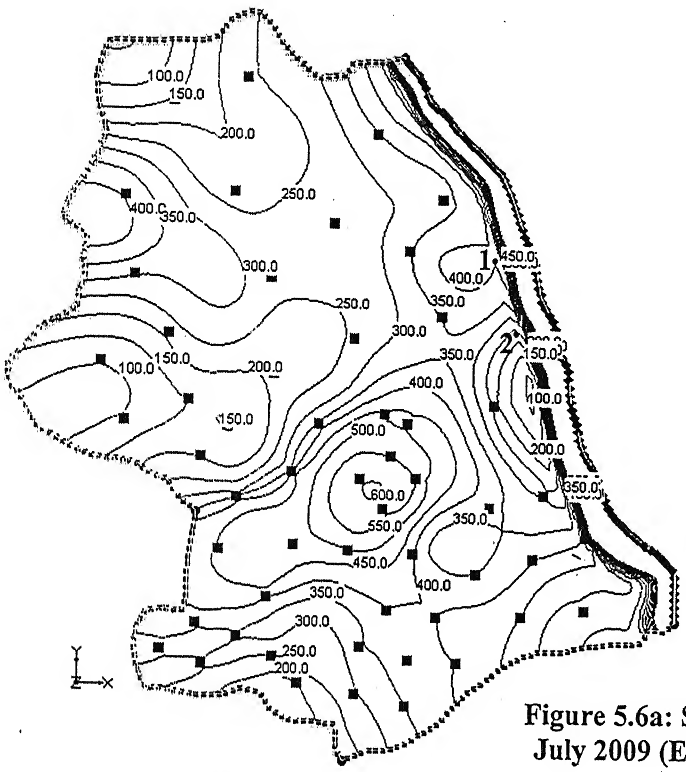


Figure 5.6a: Salt concentration contours in July 2009 (Existing old pumping pattern)

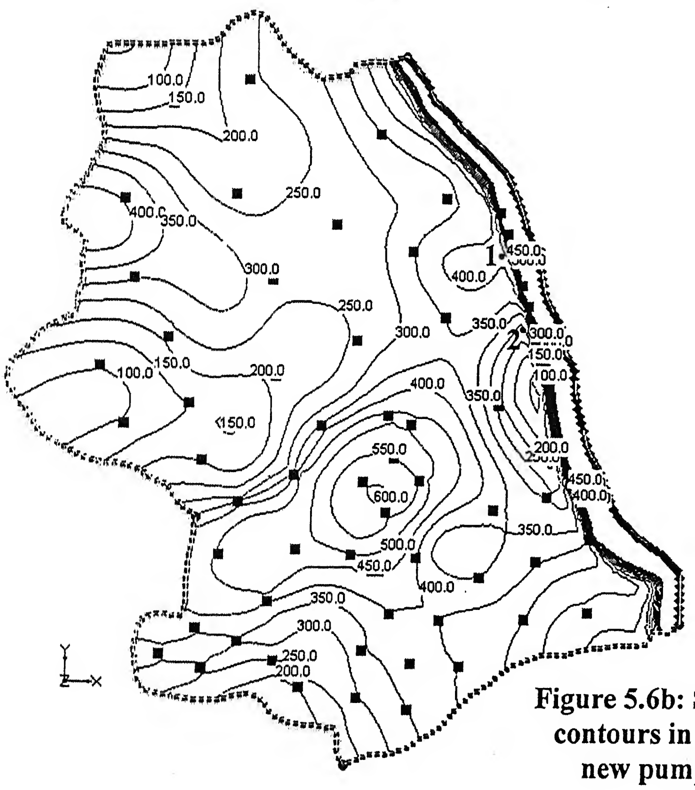


Figure 5.6b: Simulated salt concentration contours in of July 2009 (Hypothetical new pumping pattern, scenario 2)

It is observed from the above concentration contours of July 2009, shown in figures 5.6a and 5.6b, there is a decrement in concentration with additional pumping induced in some locations. Figure 5.7 and 5.8 shows concentration variation with time for the existing and new pumping patterns at different specified locations, as shown in figure 5.6b. Actually, the increasing trend in concentration is arrested in both locations 1 and 2 by inducing these additional pumping.

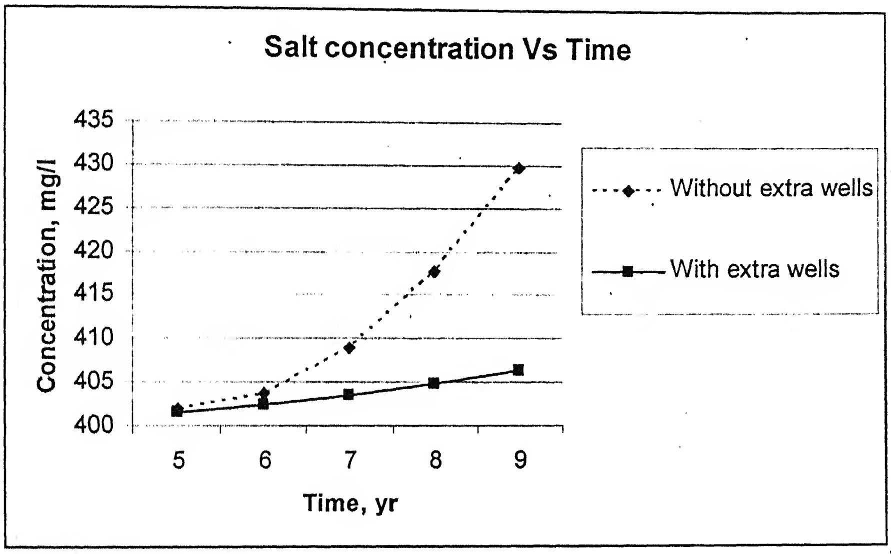


Figure 5.7: The concentration variation with time for both pumping patterns at location 1 (Scenario 2)

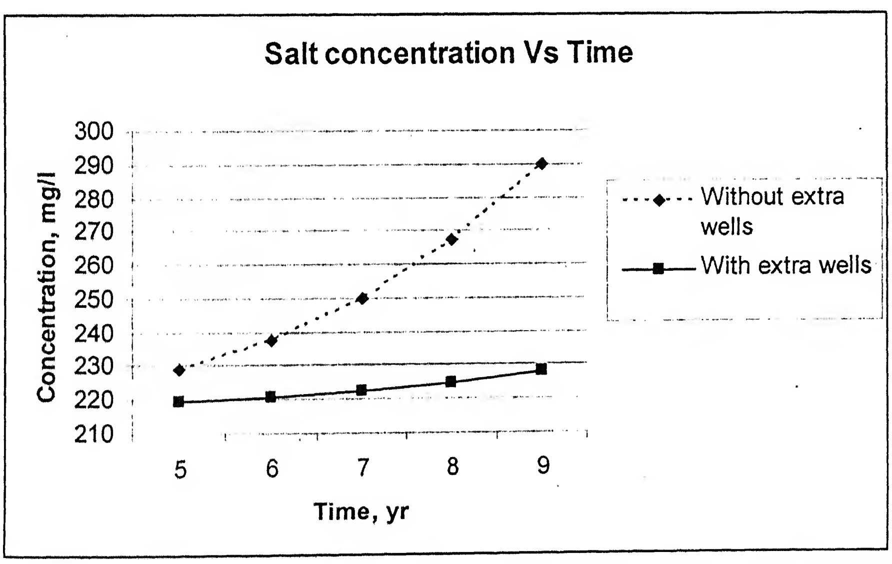


Figure 5.8: The concentration variation with time for both pumping patterns at location 2 (Scenario 2)

5.3 Scenario 3: Additional pumping wells at Dampuru village of Vidavalur Mandal.

In scenario 3, five additional pumping wells are induced at Dampuru village of Vidavalur mandal. Figure 5.9a and 5.9b shows the old and new pattern of the well locations respectively. The pumping rates in the additional wells are 3,50,0000 m^3/yr.

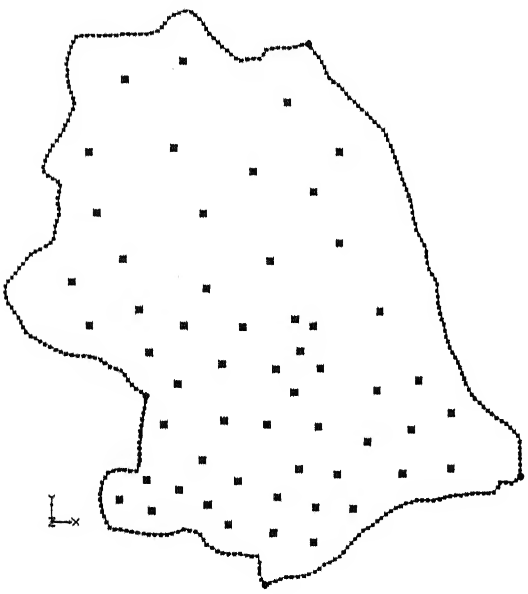


Figure 5.9a: Location of wells in existing old pumping pattern

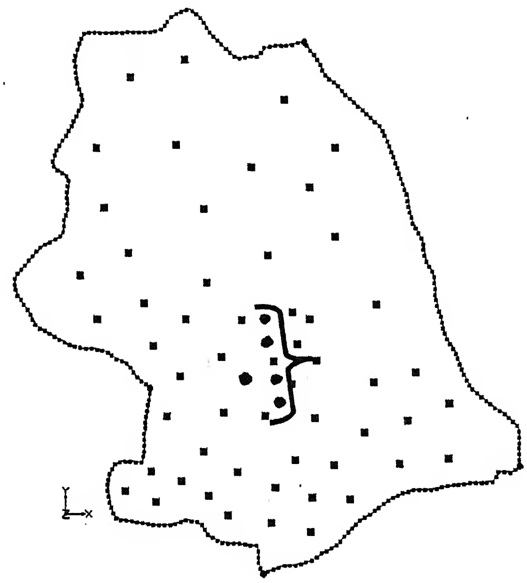


Figure 5.9b: Location of wells for new hypothetical pumping pattern (scenario 3)

The pumping in these new wells starts from the fifth year i.e., in July 2005. Figures 5.10a and 5.10b show the concentration contours after five years from July 2004, i.e. in July 2009. It can be observed from the resulting concentration contours of July 2009, that there is a decrement in concentration, with additional pumping new wells in some locations, compare to the existing pattern. In both the cases concentration is decreasing with time, but the decrement is more in the new pattern compared to the old one.

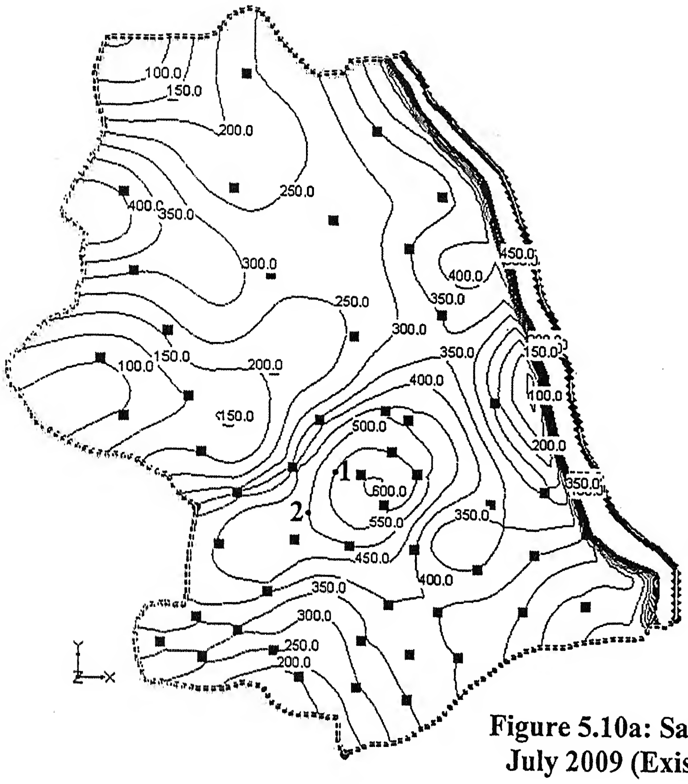


Figure 5.10a: Salt concentration contours in July 2009 (Existing old pumping pattern)

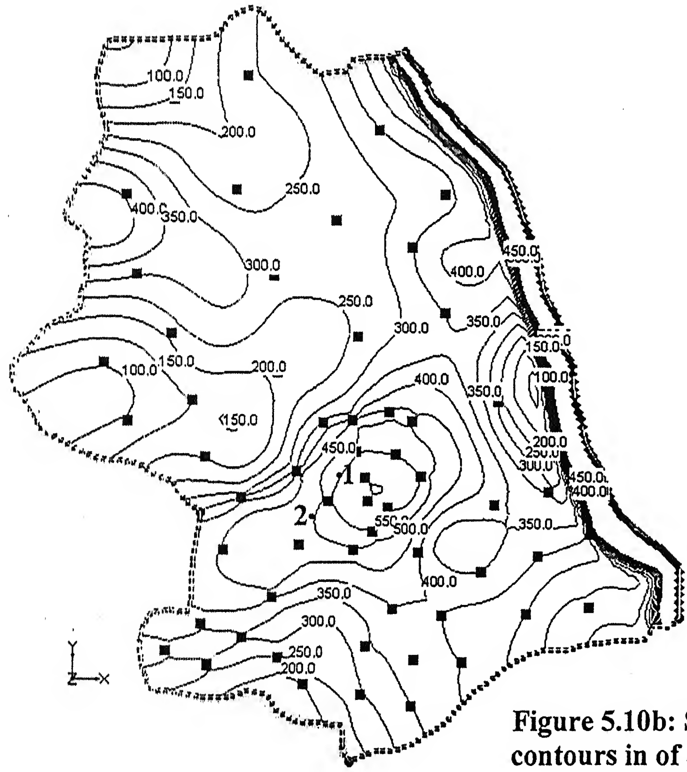


Figure 5.10b: Simulated salt concentration contours in of July 2009 (Hypothetical new pumping pattern, scenario 3)

Figure 5.11 and 5.12 show concentration variation with time in the both pumping patterns, at different specified locations, 1 and 2 for scenario 3. Evaluating results also shown that very close to the new pumping wells, the salt concentration may increase also. Similarly, on the coastal side of a series of pumping wells near the sea front, the salt concentration may also increase.

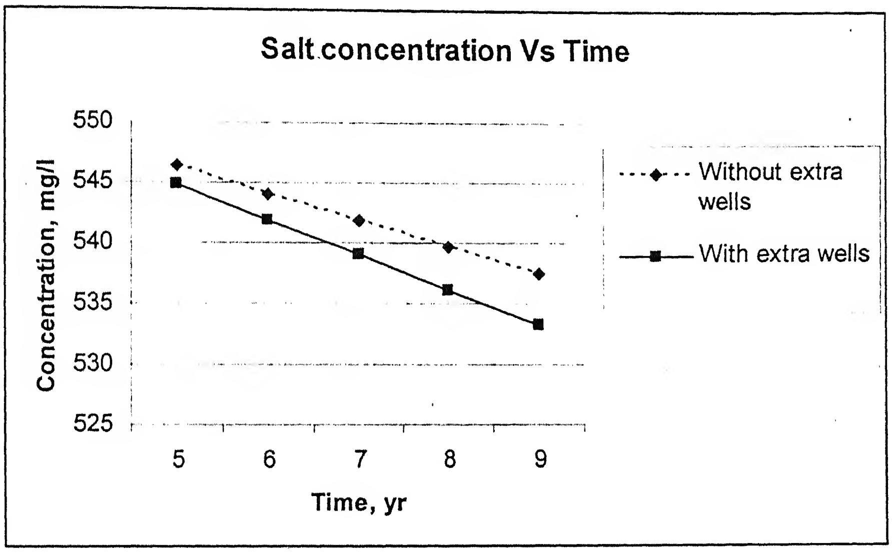


Figure 5.11: The concentration variation with time for both pumping patterns at location 1 (Scenario 3)

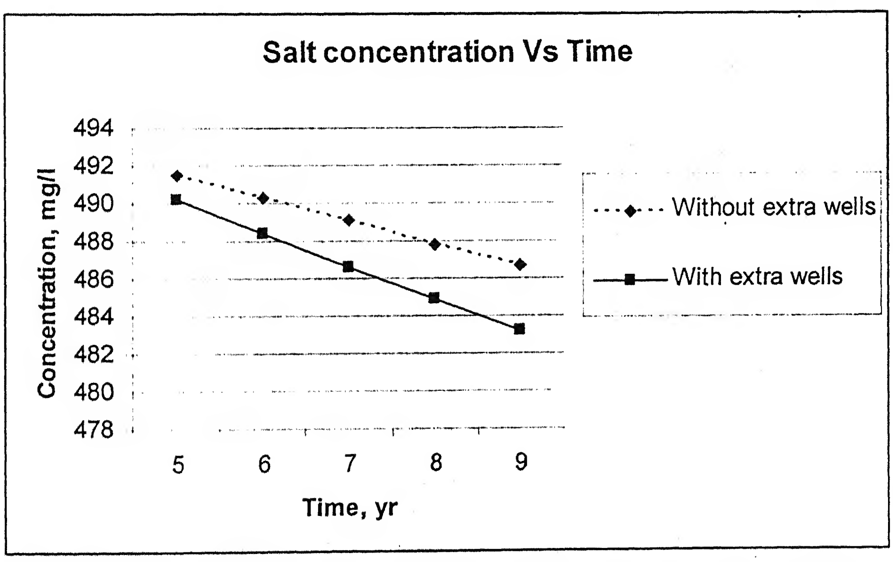


Figure 5.12: The concentration variation with time for both pumping patterns at location 2 (Scenario 3)

5.4 Scenario 4: Pumping rates increased by 10% over the previous years from July 2004 to July 2009 in all the existing wells.

The pumping rates in all the existing wells are increased by 10% over the previous year from July 2004 to July 2009. The pumping rates for July 2004, are as described before. Figures 5.13a and 5.13b show the concentration contours in July 2009.

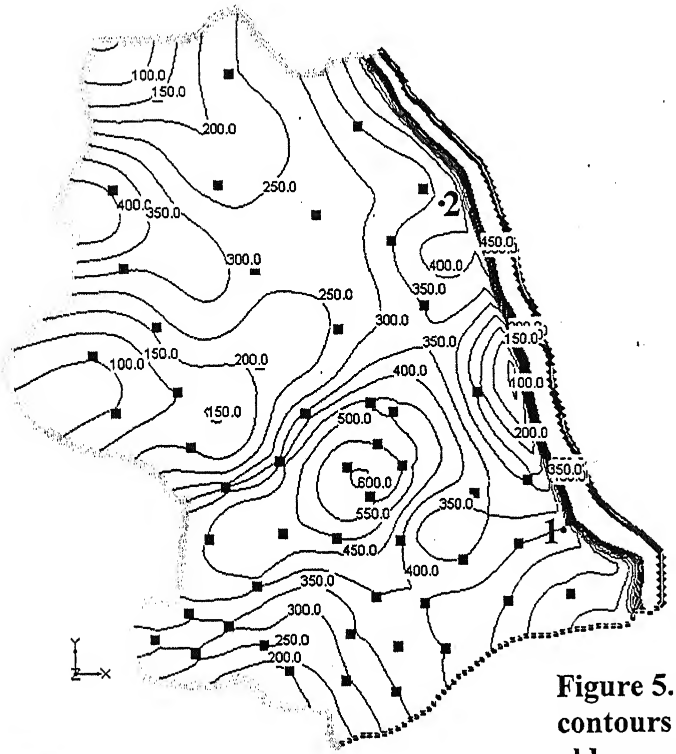


Figure 5.13a: Salt concentration contours in July 2009 (Existing old pumping rates)

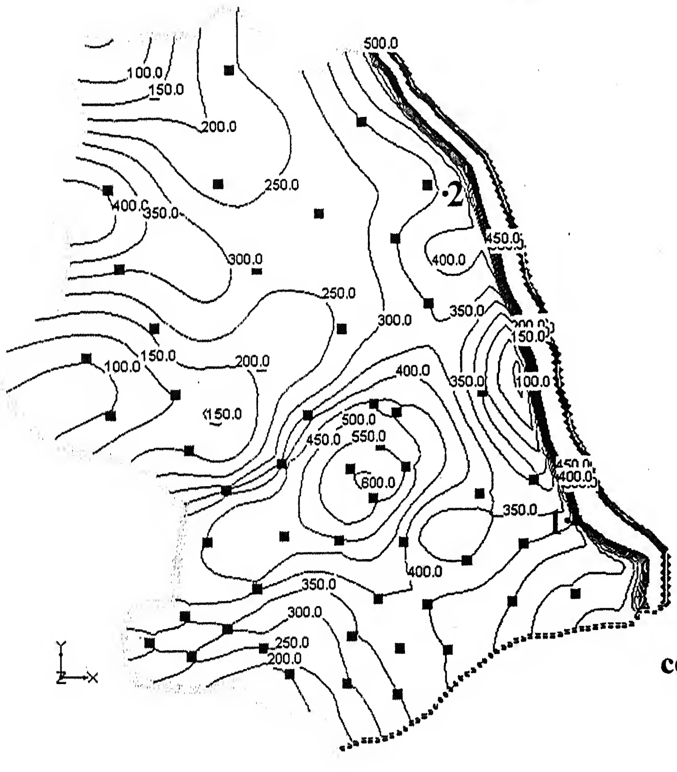


Figure 5.13b: Simulated salt concentration contours in of July 2009 (new pumping rates, scenario 4)

It is observed from the concentration contours of July 2009, there is some marginal increment in salt concentration with increase in pumping rates. Figures 5.14 and 5.15 show concentration variation for both the pumping rates at two different specified locations 1 and 2 (Figure 5.13a and 5.13b).

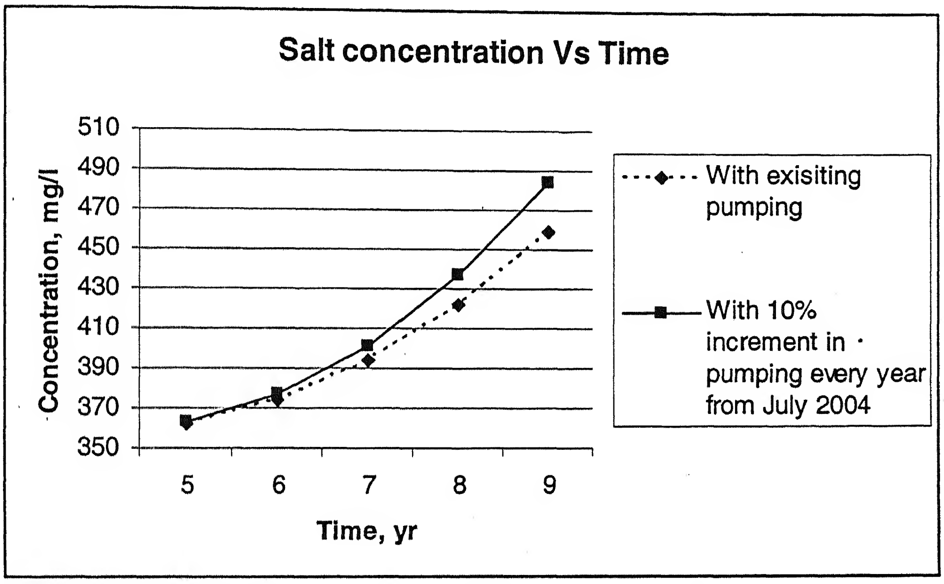


Figure 5.14: The concentration variation with time for both pumping rates at location 1 (Scenario 4)

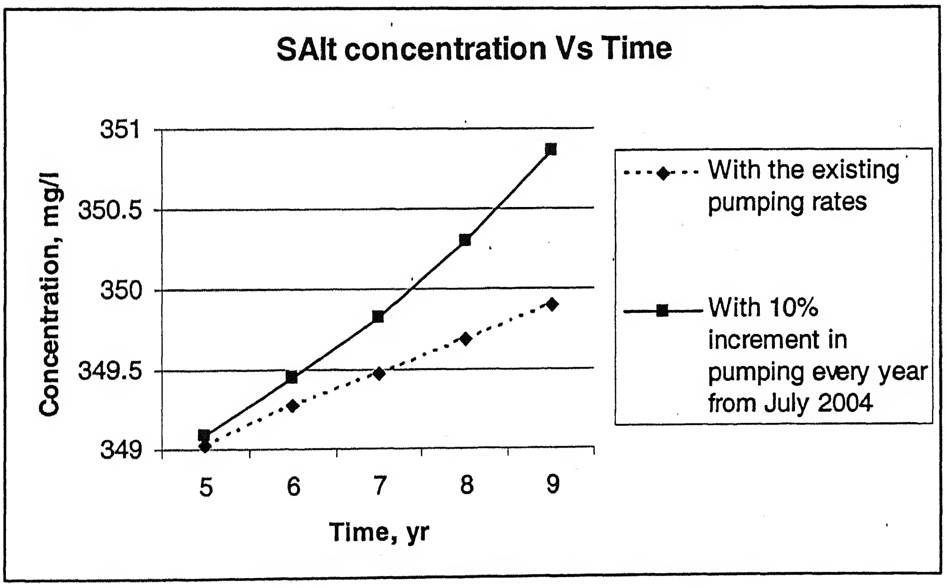


Figure 5.15: The concentration variation with time for both pumping rates at location 2 (Scenario 4)

The salt concentration values at these locations from the figures 5.14 and 5.15 show that there is an increment in salt concentration with increase in pumping rates. This trend is more near the coast line compared to other parts of the study area.

These evaluation results obtained for hypothetical pumping scenarios selected with some consideration for possible control of saltwater intrusion, no doubt establish the font that it is possible to alter the salt concentration in the aquifer by modifying the pumping patterns. These results, although very limited in scope, do show these pumping as a planned strategy can be applied to control salt concentration patterns and therefore, manage the saltwater intrusion process. These results are also useful in predicting the salt concentration scenario in the future, for existing pumping patterns.

Chapter 6

Summary and Conclusions

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A 3D, transient, density dependent, finite element based flow and transport simulation model, FEMWATER (Lin *et al.*, 1997), is implemented for simulating the coupled flow and transport processes of saltwater intrusion in a coastal aquifer in Nellore district of Andhra Pradesh, India.

Available data for a selected study area of around 355 km^2 was collected from different agencies to be used as input data for implementing the numerical simulation model for the study area. Due to the scanty nature of available data and questionable reliability of all available data the best but subjective judgment was used in selecting the data for implementing the model.

The numerical model was calibrated for two years time period, between July 2000 and July 2002, both in terms of hydraulic heads and salt concentration. The calibrated model was further validated for the chosen hydrogeological parameters with the data available between for 2002 and July 2004.

The aquifer was considered heterogeneous in terms of vertical stratification. Both flow and transport are considered transient. Withdrawal from aquifer is estimated based on available data, and assuming an increasing trend over the period of calibration and validation. The calibrated simulation model was used to predict the saltwater transport scenario in the study area at future time periods.

The simulation was carried out till July 2009. This predicted head and concentration values show the future saltwater intrusion patterns if the present trend of pumping

continues. The calibrated model was also used to evaluate the effect of modifying the pumping patterns on the future saltwater intrusion process. Effect of increase in withdrawal rates uniformly spread over the study area was also evaluated. These evaluation results show that a careful planned pumping strategy is capable of modifying the saltwater intrusion process and the spatial and temporal concentration patterns. These results show that a well planned pumping strategy can help in controlling the saltwater intrusion process in space and time. These results also show if the withdrawal rate continues to increase over time it may have detrimental effect on the salt concentration in the study area.

These evaluation results are based on very limited data and are limited in scope. Actual implementation of planned pumping strategy for economic management of the coastal aquifer will required more rigorous calibration and validation with additional reliable data. Only then the impact of any pumping strategy can be properly evaluated.

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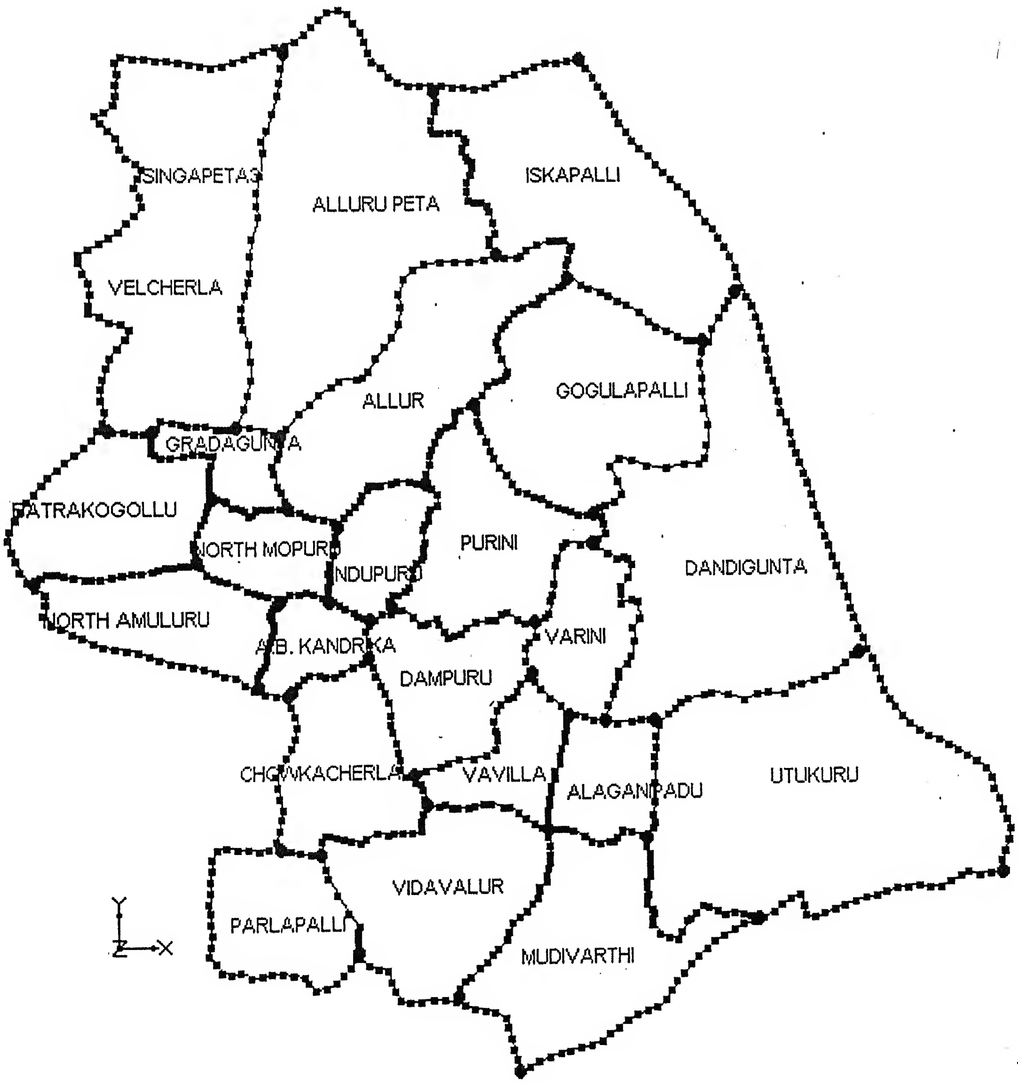
Appendix 1

Villages in the Study Area



Appendix 2

Drafts and Pumping rates in all the villages during July 2000 to July 2001

Mandal	Name of the Village	Draft between July 2000 to July 2001 (D) ha-m	Draft considered for the study (D * 1.1) ha-m	Number of wells Considered	Initial (July 2000) Pumping rate in each well 10^4 m^3 /yr
Vidavalur	Parlapalli	129.3	142.2	3	47.4
Vidavalur	Chowkicherla	100.4	110.4	2	55.2
Vidavalur	Mudivarthi	652.4	717	7	For 1 well , 123.6 Rest 6 wells, 99
Vidavalur	Vidavalur	417	459	5	91.8
Vidavalur	Dandigunta	35	38.4	1	38.4
Vidavalur	Utukur	433	476.3	7	For 2 wells, 79.2 Rest 5 wells, 63.6
Vidavalur	Alaganipadu	35	38.4	1	38.4
Vidavalur	Vavilla	162.5	178.8	2	89.4
Vidavalur	Dampur	99.3	109.2	1	109.2
Vidavalur	Varini	462.5	508.8	6	For 1 well, 100.8 Rest 5 wells, 81.6

Mandal	Name of the Village	Draft between July 2000 to July 2001 (D) ha-m	Draft considered for the study (D * 1.1) ha-m	Number of wells Considered	Initial (July 2000) Pumping rate in each well 10^4 m^3 /yr
Allur	Allurupeta	36	39.6	2	19.8
Allur	Singapeta	14.2	15.6	2	7.8
Allur	Velicherla	4.4	4.8	1	4.8
Allur	Iskapalli	79.6	87.6	2	43.8
Allur	Alluru	98.2	108	2	54
Allur	Graddagunta	12	13.2	1	13.2
Allur	Batra Kagollu	15.3	16.8	1	16.8
Allur	Gogulapalli	100.4	110.4	2	55.2
Allur	Purini	33.8	37.2	2	18.6
Allur	Indupuru	25	27.6	2	13.8
Allur	North Amuluru	36.4	40	1	40
Allur	North Mopuru	45.8	50.4	1	50.4
Allur	A. B. Khandriga	23	25.2	1	25.2